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Sustainability analysis in the mining sector: a case study on new recycling technologies for sulphidic mine residues valorisation

Tesi di Laurea in Environmental impact, LCA and urban mining

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Sommario

Abstract

Research has demonstrated that mining activities can have a serious impact on the environment, as well as the surrounding communities. The recovery of metals from mine tailings may represent an opportunity for mining companies to reduce the environmental and social impact of their activities and increase the profitability.

This research focuses on the sustainability assessment of new technologies for the recovery of metals from mine residues. The assessment consists in the evaluation of the environmental, economic, and social impacts through the Life Cycle based methods: Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA). The analyses are performed on the Mondo Minerals bioleaching project, which aim is to recover nickel and cobalt from the Sotkamo and Vuonos mine tailings.

The LCA demonstrates that the project contributes to the avoided production of nickel and cobalt concentrates from new resources, hence reducing other several environmental impacts. On the other hand, the bioleaching process contributes the most to the environmental impacts derived from the implementation of the plant, mainly due to the electricity consumption.

The LCC analysis shows that the company's main costs are linked to the bioleaching process, caused by electricity consumption and the chemicals used.

The SLCA analyses the impacts on three main stakeholder categories: workers, local community, and society. The results demonstrated that a fair salary (or the absence of it) impacts the workers the most, while the local community stakeholder category impacts are related to the access to material resources. The health and safety category is the most impacted category for the society stakeholder.

The environmental and economic analyses demonstrate that the recovery of mine tailings may represent a good opportunity for mine companies both to reduce the environmental impacts linked to mine tailings and to increase the profitability. In particular, the project helps reduce the amounts of metals extracted from new resources and demonstrates that the use of the bioleaching technology for the extraction of metals can be economically profitable.

The conduction of three analyses in parallel is useful to identify the common hotspots and the trade-offs between the environmental, economic, and social point of view. Moreover, it can be helpful for the implementation of the Mondo Minerals' project because the company can decide if and where are the main hotspots and where it should focus to improve the plant performances.

The three different analyses do not highlight the chain and interconnected relationships between the three dimensions of sustainability. Thus, further implementation must focus on the development of a common framework to assess the sustainability of a product, service, or project from all the sides when presenting these same results to decision-makers.

Riassunto

La ricerca ha dimostrato che le attività minerarie possono avere un grave impatto sull'ambiente, così come sulle comunità circostanti. Il recupero dei metalli dagli scarti di miniera può rappresentare un'opportunità per le compagnie minerarie per ridurre l'impatto ambientale e sociale delle loro attività e aumentare la redditività.

Il presente studio si pone l'obiettivo di valutare la sostenibilità dell'utilizzo di nuove tecnologie per il recupero dei metalli dai residui di miniera. Lo studio consiste nella valutazione degli impatti ambientali, economici e sociali attraverso i metodi basati sul ciclo di vita: Life Cycle Assessment (LCA), Life Cycle Costing (LCC), e Social Life Cycle Assessment (SLCA). In particolare, come caso studio specifico è stato analizzato il progetto di bioleaching di Mondo Minerals, che si pone come obiettivo il recupero di nichel e cobalto dai prodotti di scarto delle miniere di Sotkamo e Vuonos (Finlandia).

L'analisi ambientale (LCA) dimostra che il progetto contribuisce a ridurre l'estrazione di nichel e cobalto da nuove materie prime, grazie al recupero dei metalli attraverso la tecnica di bioleaching. Questo permette di evitare gli impatti ambientali derivati dal consumo delle risorse necessarie all'estrazione. D'altra parte, il processo di bioleaching contribuisce maggiormente agli impatti ambientali derivati dall'implementazione dell'impianto, principalmente a causa del consumo di elettricità.

L'analisi economica (LCC) dimostra che i principali costi dell'azienda sono legati al processo di bioleaching, a causa principalmente del consumo di elettricità e dei prodotti chimici utilizzati.

L'analisi sociale (SLCA) analizza gli impatti su tre principali categorie di stakeholder: lavoratori, comunità locale e società. Dai risultati è emerso che un salario equo (o l'assenza di esso) impatta maggiormente sulla categoria dei lavoratori. Invece, gli impatti sulla categoria della comunità locale sono legati all'accesso alle risorse materiali, mentre la categoria salute e sicurezza è la categoria più impattata per quanto riguarda la società.

Le analisi ambientali ed economiche dimostrano che il recupero degli scarti di miniera può rappresentare un'opportunità per le società minerarie, sia per ridurre gli impatti ambientali legati agli scarti stessi, sia per aumentare il profitto dell'impresa.

La conduzione delle tre analisi in parallelo è utile per identificare quali potrebbero essere i principali processi che rappresentano i maggiori impatti dai diversi punti di vista: ambientale, economico e sociale. Inoltre, l'analisi può essere utile per l'azienda Mondo Minerals, in quanto è in grado di valutare se e dove potrebbe concentrarsi per migliorare le prestazioni dell'impianto.

D'altra parte, le tre diverse analisi non evidenziano le relazioni che intercorrono tra gli impatti ambientali, economici e sociali. Pertanto, risulta necessario sviluppare una metodologia che permetta di valutare la sostenibilità di un prodotto, di un servizio o di un progetto da tutti i punti di vista.

Introduction

Sustainability in the mining sector

The concept of sustainability, used since the 80s, is becoming more and more important worldwide, especially in the last decades.

The definition of sustainability is strictly correlated to the definition of sustainable development. The United Nations Brundtland Commission of 20 March 1987, first described sustainability development as “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (Visser & Brundtland, 2013).

In June 1992, at the Earth Summit of Rio de Janeiro, more than 178 countries adopted the Agenda 21, an action plan to protect the environment and build a global partnership for sustainable development.

The industrial sector is facing the challenge to move towards a more sustainable and circular business model, due to the increasing need for new solutions to limit the earth resources depletion and climate changes. The transition towards a greener economy also demands for the development of new technologies, that aim to help the reduction of fossil fuel use and carbon emissions. However, these new technologies are highly dependent on the production of metals, usually zinc, manganese, and rare earth metals that are currently extracted through mining activities. Therefore, mining companies play an important role in providing these metals for developing technologies to achieve climate change reduction in the near future.

The adoption of the 17 Sustainable Development Goals (SDGs) at the UN Sustainable Development Summit of 2015 is an opportunity for mining companies to improve the environmental and social impacts of their processes. Actually, many of the Sustainable Development Goals cannot be reached without the contribution of minerals and metals production (Mancini & Sala, 2018).

Mining companies, as reported by the Columbia Center on Sustainable Investment (2016), can support many SDGs, for instance:

- SDG1 (“End poverty”). By the payment of taxes to the government and the creation of job opportunities, mining contributes to the eradication of poverty, encouraging the development of the country through the development of infrastructure, housing, education, and healthcare services. Mining companies must also ensure the access to natural resources for the communities close to the mine.
- SDG2 (“Zero hunger”). Mining industries often operate in places where agriculture is one of the main livelihood sources. Their presence can affect the quality of water, contaminates

soil, and compromises the production of essential food. Therefore, mining companies can contribute to SDG2 by reducing the impacts on the surrounding environment, avoiding social conflicts with the local communities (Columbia Center on Sustainable Investment, 2016).

- SDG3 ("Good health and well-being"). This is a critical goal for mining companies. In the latest years they have seriously committed to improve their safety and health measures, both in the short- and long-term period, by stabilizing standards and managing system.
- SDG4 ("Quality education"). Mining can contribute to this goal through the education and technical training of the employees, encouraging the increase of expertise of the local workers.
- SDG5 ("Gender Equality"), and SDG10 ("Reduce inequalities"), to create new social opportunities and fighting inequalities.
- SDG6 ("Clean Water and sanitation") and SD15 ("Life on land"), by the "implementation of new technologies aiming at an efficient waste water treatment and at the reduction of the land consumption for tailings treatment and storage facilities"(Di Noi & Ciroth, 2018).
- SDG8 ("Decent work and economic growth"), through local procurement, which can benefit the economies of affected communities, especially during the pandemic of COVID-19, that limits the effectiveness of international supply chains.
- SDG12 ("Responsible consumption and production"). Mining industries can contribute to implement this goal by minimizing their wastes and move toward the circularity of their products, by reuse, recycling and repurpose of metal and minerals. These actions represent an opportunity for the sector, enhancing the job creation and the industrial innovation (Columbia Center on Sustainable Investment, 2016).

Figure 1.1 Major issue areas where mining can have an impact, foe each SDG (Columbia Center on Sustainable Investment, 2016).

Mining companies can bring numerous benefits in the area where they operate, especially in developing countries. For example, they can increase the employability (directly or indirectly) at both local and national level. The presence of mining industries can boost the income opportunity for the local businesses and the local population. Educational opportunities offered by the company are further potential positive outcomes (Mancini & Sala, 2018). New mining projects can also promote education and provide infrastructures and access to medical services for the communities (Githiria & Onifade, 2020).

Nevertheless, the extraction processes are the cause of many environmental and social impacts worldwide (Watari et al., 2021). For example, if the benefits derived from the extraction of metals are not equally distributed, mining activities can lead to the exacerbation of social tension (Mancini & Sala, 2018).

Mining projects, especially in developing countries, may negatively impact local traditions. In fact, these activities often operate in traditionally self-sustaining communities. They can provide food for themselves through farming, fishing, and hunting. Unfortunately, the introduction of these industries slowly leads to the reduction of these traditions. The result is the complete dependence of local population on the mines (Githiria & Onifade, 2020; Richards, 2009).

In addition, negative social impacts can occur with the presence of child labour and forced labour (or dangerous and poor conditions) and the violation of human rights, through the discrimination of vulnerable groups, disrespect of indigenous population, gender inequality and abuse of child work (Mancini & Sala, 2018).

These impacts are especially located in developing countries, where mine companies presence and behaviour are not well controlled by governments and laws. On the contrary, the European union ensures that mining activities and mining waste are managed properly, thanks to a combination of environmental and human rights laws (Scannell, 2012)

Indeed, when not well managed, mining activities can contaminate rivers, lakes, and soil. The contamination can lead to the reduction of water supply and the loss of fishery income, which is the main source of income for local population in certain areas.

The environmental impacts have negative effect also on the local and regional level. Once the contamination has occurred, the remediation costs and the effect on ecosystem and human health are huge (Mancini & Sala, 2018).

For these reasons, mining companies are not well-seen by NGOs and local communities. For example, in Brazil and Latin America there are many conflicts between the local population and mining companies, which are becoming a real challenge for the mining group in the region (Perez & Sanchez, 2009).

It is important to distinguish, while considering the social impacts of the mining sector, between large-scale mining (LSM) and artisanal and small-scale mining (ASM). Usually, although small in scale, ASM are generally responsible of greater environmental and social impacts than LSM. Indeed, ASM usually lacks of management of processes in terms of environmental and social impacts (Lodhia, 2018).

The COVID-19 pandemic is having a disproportionate impact on ASM miners and their communities. They are even more vulnerable than they were before, due to factors such as low commodity prices, risks of contracting the virus and government restrictions which combined are putting their livelihoods and wellbeing at risk (Hilson et al., 2021).

Since the last decades of twentieth century, large mining companies are facing several pressures to improve their sustainability, since the contribution of the sector to the transition towards a more sustainable economy and society can be significant. Therefore, the transparency, accountability, and credibility of mining sustainability reports must be carefully considered.

An important role resides in governments, that can be drivers towards the improvement of sustainable reporting from mining industries through their policies. Governments can engage with mining companies and other stakeholder to better define their role in the transition to a greener economy, considering the context of the sector in the country (Lodhia, 2018).

Sustainability reports in the mining sector

Around 93% of the world's 250 largest companies (by revenue) disclose information regarding their environmental and social performances ((Perez & Sanchez, 2009). Most reporting companies refer to the reporting framework of the Global Reporting Initiative (GRI).

However, due also to the different reporting framework, most of these sustainability reports are not sufficiently complete. The overall quality of the sustainability reports from mining companies, as reported in the Responsible Mining Index of 2020, is still poor (RMF, 2020).

The reports do not allow to have a complete and meaningful conclusion on what are the main environmental and sustainable impacts of the mine companies.

Generally, sustainability reporting also lacks in the description of positive externalities, especially at site-level, such as the employment of local communities and the creation of opportunities for local suppliers. These are key elements of interest for communities, workers, investors and governments (Lodhia, 2018). Several international organisations and initiatives are focusing on encouraging mine companies to report the sustainability performances at site-level.

Sustainable mining in Europe

As previously stated, the increased need of new renewable technologies to move towards a low-carbon society prompt the demand for minerals and metals.

Since the first years of the twenty-first century, the demand was driven by growing economies as China, which consumes 50% of global iron production and 30% of global copper and aluminium (Vidal et al., 2013). China has also the largest REE (Rare Earth Elements) reserves in the world (Charalampides et al., 2015), thus is the major producer of REE in the world and leads the market of metals.

There is a discrepancy between the region of production of metallic minerals and the places of consumption (Tiess, 2010). Europe is one of the major importer of metallic minerals from extra-European countries (Brown et al., 2016; Tiess, 2010), although in the eighteenth and nineteenth centuries was self- sustaining in term of metal extraction. In fact, European countries consume around the 20-30% of the global consumption of metals, but produce only 3% of global production (Brown et al., 2016; Nurmi, 2017; Tiess, 2010).

Thus, European Union is far from being self-sustaining in terms of metals supply. On the other hand, mineral based production industries (such as, manufacturing and building) have an important role in Europe, providing jobs for more than 30 million people (Nurmi, 2017). The dependence from the minerals supply from other countries makes these industries vulnerable to the fluctuation of the supply and the prices of the materials.

To move towards a greener economy and technologies, European countries should consider investing in urban mining. This should reduce the environmental impact due to the transportation of materials from extra-European countries. In addition, it should avoid the impacts in places where mining activities are not controlled and cause serious damage to environment and local communities.

Technological innovations have unlocked the possibility to recover metals from previously uneconomic low grade ores (Vidal et al., 2013). Urban mining, for example, represents a precious source of metals: discarder electronic can be processed locally in Europe in order to recover materials and metals, in a circular economy concept, instead of shipping them to Asia for processing (Vidal et al., 2013).

Mine tailings represent another potential source of valuable metals. Mine tailings are the leftover material from the processing of mine minerals, and are composed by silicates, oxides, hydroxide, carbonate and sulphides, water, and other processing fluids (Beylot & Villeneuve, 2017). Usually, mine tailings are stored in big ponds close to the mine site. If not well managed, tailings can be source of great environmental impacts, contaminating water and soil and causing serious damages to the biological lives of the area surrounding the mine(Park et al., 2019).

To avoid these impacts and reduce waste mining handling costs, in recent years different projects are proposing bioleaching as a promising process to extract valuable metals from mine tailings, such as nickel, copper, zinc, and rare earth metals. It consists in the solubilisation and the extraction of metals from low grade ore (like mine tailings) thanks to the activity of microorganisms (usually bacteria and fungi).

To make sure that this process is sustainable, its impacts must be evaluated from the environmental, economic, and social point of view.

One of the ways to assess the environmental implications of the technology is the Life Cycle Assessment (LCA). Social Life Cycle Assessment (SLCA) and Life Cycle Costing (LCC) are methodologies derived from LCA that aim to evaluate respectively the social and the economic impacts of products and services.

Life Cycle Thinking

Life Cycle Assessment is a standardised method consisting in the evaluation of the entire life cycle of a good or a service, in terms of environmental impacts (European Commission, 2010). The aim of LCA is to quantify and assess the most relevant activities and processes, implied with the analysed good or service, that are relevant for the environment, such as the extraction of the raw materials, manufactory, transportation, and distribution, recycle, upcycle and disposal.

Considering the whole life cycle of a product helps to avoid "burden shifting", meaning to resolve an environmental problem in one life cycle phase while creating others in other phases.

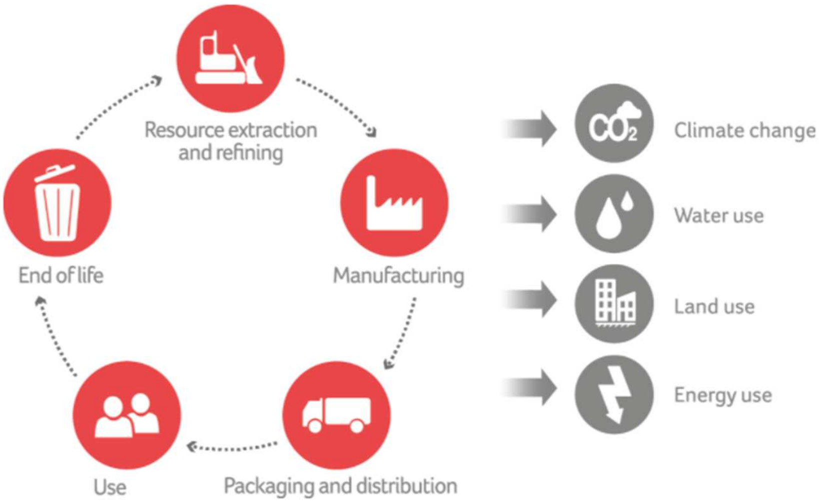


Figure 1.2. The life cycle of products (ecoinvent.org)

Social Life Cycle Assessment aims at assessing the potential social and socio-economic impacts of product or service during the entire life cycle (SETAP, 2009).

The Guidelines for S-LCA for products in May 2009 (UNEP, 2009) implemented the S-LCA methodology. The proposed structure is in line with the ISO 14040 and 14044, but it is adapted to the social aspects. The S-LCA guidelines have been recently updated (UNEP Setac Life Cycle Initiative, 2020).

The goal of S-LCA is to promote the improvement of the product's social performances along all its life cycle, on all stakeholders involved. S-LCA can be used as a support for decision making (social politics definition, solidarity between generations, etc.), for the creation of social reports and financial statements and for the social risk management.

Life cycle costing, or LCC, is a compilation and assessment of all costs related to a product, over its entire life cycle, from production to use, maintenance and disposal (Fabrycky et al., 1998).

The main costs that need to be considered in a LCC are (Estevan & Schaefer, 2017):

- Manufacturing
- Use
- Disposal
- Research and Development.

Life Cycle Thinking methods applied to the mining sector: literature review

As previously stated, mining activities can cause different damage to the areas surrounding the mine site. The degree of these impacts varies from a mine to another, depending on the type of ores, the metals extracted and the volume of production (Farjana et al., 2019). To move towards more sustainable mining, it is firstly necessary to identify which are the processes and operations that contribute the most to the environmental impacts.

The analysis of the environmental impacts is the aim of the Life Cycle Assessment approach: mining industries can use LCA as a tool to support decisions that aim to minimize the overall environmental impacts of their own process (Lesage et al., 2008).

In the mineral and mining sector, a few significant researches are focused on the LCA of specific mining processes. However, these studies differs from one to another, depending on the database used, the impact calculation method and the metals extracted.

During an LCA analysis, it is important to define the system boundaries, to identify the processes and the life cycle phase of a product that must be included in the assessment. Usually, the system boundaries considered in mining based LCA studies are assessed from the extraction of raw material to the factory gate ("from cradle to gate"), due to the lack of data source on the end of life of the processed metals.

In the study of Mistry et al. (2016), the Nickel Institute (NI) conducted a global LCA study on nickel products to evaluate the potential environmental impacts of nickel and ferronickel production from mining to refinery gate. Nine companies contribute to the data, representing the 52% of global nickel metal production and 40 % of global ferronickel production (Mistry et al., 2016). The results show that the primary extraction together with the refining processes were the first contributor to the impact categories Global Warming Potential (GWP) and Primary Energy Demand (PED). The most significant contributor to the primary extraction process was the electricity consumption (35% for PED and 48% of GWP) (Mistry et al., 2016).

Another LCA study from T. E. Norgate et al. (2007), investigated the environmental impact of metal production processes of different metals (Cu, Ni, Zn, Pb, Al). The results show that the lighter metals, namely the titanium and aluminium, had the greatest “cradle to gate” environmental impacts in terms of GWP and AP (Acidification Potential), followed by nickel. Steel and lead had the lowest environmental impacts in this terms (T. E. Norgate et al., 2007). From the results emerged also that the ore grade greatly influences the environmental impacts of the mining processes. The increase of mined high-grade ores leads to the depletion of ores, that need larger energy consumption and results in the increase of greenhouse gases and acid rain emissions. The depletion of ore grades will result in an increase in the amount of mine tailing material that must be handled and disposed of, thereby increasing the environmental impacts of metal production (T. Norgate & Haque, 2010).

The type of energy used also influences the environmental impacts of mining processes (Farjana et al., 2019).

A Life Cycle Assessment study highlights the ferronickel production in Greece as an energy intensive metallurgical operation (Bartzas & Komnitsas, 2015). The results show massive greenhouse gases emissions (GHG) and solid wastes. The stages contributing to the highest impact were the smelting and refining, followed by ore mining beneficiation (Bartzas & Komnitsas, 2015).

Most of the considered LCA studies focus on the evaluation of mine operation (Lesage et al., 2008). There still are not many studies on evaluation of the industrial waste handling and, even in the most comprehensive databases, like Ecoinvent, the sulphidic tailings management process considers only the occupation of land. Emissions from the tailings over time and the energy and material requirements for sulphidic tailings management are not yet considered (Lesage et al., 2008).

Only few studies focus on the assessment of the environmental impacts of mine tailings. For example, a study conducted by BRGM (Beylot & Villeneuve, 2017), aimed at assessing the impacts of copper mine tailings through a LCA, considered the toxic-related environmental impact categories. They concluded that, in dependence to the time horizons considered, the impacts related to the disposal of sulphidic tailings “may be several orders of magnitude larger than those of copper concentrate production” (Beylot & Villeneuve, 2017).

Another study aims at quantifying and comparing the impacts related to six different mine tailings management methods in Quebec (Canada), and assessing the contribution on the land use impact category (Reid et al., 2009). The main conclusions state that the closure option (cover with capillary barrier effects) is the most harmful one, as it requires seeds production and a greater machinery work. The tailings disposal and backfill plat option have higher impact in most of the impact categories considered, due to the consumption of a great amount of material and energy (Reid et al., 2009). The results demonstrate that the consideration of the land use impact category and the long-term impacts are important when evaluating the environmental impacts of mine tailings over time.

In conclusion, despite there have been many LCA studies in the mining sector, the methodology may still need to be better developed as different types of relevant impacts for the mining sector are not well defined. For example, there are many debates regarding the inclusion of the land use impact category in the LCA studies. In the context of mining, however, the exclusion of this category may affect the credibility of the LCA studies, considering that mining can extensively damage the land (Yellishetty et al., 2009). Additionally, there have been some debates about the time perspective to apply when considering the scarcity of minerals (Yellishetty et al., 2009).

Another aspect to consider is that so far there is no study which focuses on the evaluation of environmental impacts of valuable metal recovery from mine tailings.

Building on these needs, the present LCA study identifies the impacts of the technology proposed and the trade-offs between the environmental impacts and the benefits derived from the avoided landfilling of mine tailings.

The Social Life Cycle Assessment (S-LCA) assesses social and socio-economic impacts along the life cycle, using generic and site-specific data.

To identify the main social hotspots, two main databases have been developed:

- The Social Hotspot Database (SHDB): allows modelling of social impacts and risks and covers 22 social topics for numerous countries and sectors (Mancini & Sala, 2018).
- The Product Social Impact Life Cycle Assessment (PSILCA) database. It uses a multi-regional input/output database to develop indicators on social impacts, organized in clusters. They describe 25 social and socio-economic topics inspired by UNEP/SETAC guidance.

Only few studies focus on the social impact analysis of mining operations.

A study conducted on six new mines in Northern Finland discusses how Social Impact Assessment (SIA) has been conducted, as part of Environmental Impact Assessment (EIA). The study highlights the lack of a theoretical and methodological framework. Additionally, an absence of the local population’s participation has led the SIAs to be described inadequately because it does not describe nor the benefits or the disadvantages among the local communities (Suopajärvi, 2013).

A recent article published by Di Noi & Ciroth (2018), aims at identifying through a social hotspot screening using PSILCA, the main social high risks linked to the mining sector in Finland and Portugal. Both countries present a very high risk of mining companies’ involvement in corruption and bribery, and of a socially irresponsible behaviour in the supply chain. Industrial water use emerged as an important issue for the Finnish sector. Women discrimination in the labour could be considered as social issue in the Portuguese industry (Di Noi & Ciroth, 2018).

Another S-LCA study analyses the social impacts of the rare earth metals production, in particular the ones employed in permanent magnets (rare earth iron boron magnets (NdFeB)) (Werker et al., 2019). It emerges that the magnet production and beneficiation and the separation phases contribute the most on the impacts caused by the process chain (Werker et al., 2019). The chemical sector contributes the most to the public sector corruption during the beneficiation and the separation phases (Werker et al., 2019).

Overall, it results clear that the S-LCA method still needs to be further implemented in terms of data availability. Future studies focusing on site-specific social analysis may integrate and expand the PSILCA database to make it more complete.

Only few studies focus on the Life cycle Assessment (LCC) analysis in the mining sector.

Vieira et al. (2016) study derive a characterization factor for resource scarcity, which reflects the surplus cost potential due to a unit increase in metal extraction (Vieira et al., 2016). The surplus costs may be used in environmental LCC, emphasising the importance of the metals scarcity for future metal extractions (Vieira et al., 2016).

Adiansyah et al (2017) estimates the financial value of different dewatering technologies options for the coal mine tailings treatment. The cost analysis is based on Life Cycle Costing and environmental sustainability evaluation (Adiansyah et al., 2017). The results show that the best option uses renewable energy and has low electricity consumption. Consequently, it has the higher benefit value and the lowest LCC values. As reported by the author, the study highlights the importance of considering the economic analysis while evaluating the sustainability of a tailings disposal method (Adiansyah et al., 2017).

Considering the scarcity of LCC studies dedicated to the mining sector, this thesis wants to provide a financial LCC analysis of a bioleaching plant project that aims at the recovery of metals.

Currently, there are no studies focusing on developing a sustainability analysis of mining activities, assessing the environmental, social, and economic impacts.

Most of the studies based on the Life Cycle Thinking approach focus on the LCA of different mining activities, without considering the social and/or the economic implications.

For example, Di Noi & Ciroth (2018) study , assess the environmental and social impact of the mining sector in Finland and Portugal, without considering the economic benefits (and costs) of the sector in each country.

Few studies pinpoint the impacts of mine tailings management. The Beylot & Villeneuve (2017) study assesses the environmetal impacts of copper sulphidic tailings disposal, highlighting the importance of these impacts in relation to the copper concentrate production.

Only Adiansyah et al (2017) estimates the best coal tailings management method basing on a LCC and an environmental analysis, a previously reported.

Hence, the aim of this thesis is to provide a first indication of the trade-offs between the environmental, social, and economic benefits and costs of the metal recovery from sulphidic mine tailings.

Conclusions

Mining industries face many challenges, both from an environmental and social points of view.

The increasing competition with other interests for the society, such as the awareness of protection of biological diversity, recreation, tourism, makes the competition for the mineral exploration of new areas even harder (Nurmi, 2017). Therefore, in recent years the idea of recycling mine tailings to recover valuable metals has been explored, to reduce both the environmental impacts of tailings and the extraction of new resources.

To evaluate the sustainability of these new technologies, it is necessary to evaluate the environmental, social, and economic feasibility.

Whit this purpose, this thesis will develop a simplified sustainability analysis through the LCA, S-LCA and LCC methodologies, using the Mondo Minerals bioleaching plant project as a case study. It will provide a first indication of the trade-off between the environmental impacts and the benefits derived from the recovery of metals and the avoided landfilling of sulphidic mine residues.

The economic analysis will identify the economic flows that are expected to be involved in the future development of the technologies.

The social assessment, based on the S-LCA approach, will identify some of the potential effects linked to the implementation of the technology (for instance on working conditions, environmental health, social benefits for the local communities, social responsibility).

Methods

In the last years, several pilot studies focus on the extraction of valuable metals from mine tailings. The aim is to reduce the need to extract minerals and metals from new resources.

As previously said, the use of these materials is crucial for the transition towards a sustainable economy.

Therefore, this thesis proposes to assess the actual sustainability of the mine tailings metal recovery using the Life Cycle Thinking approach.

The three methodologies used in this study are Life Cycle Assessment, Social Life Cycle Assessment and Life Cycle Costing.

Life Cycle Assessment

The Life Cycle Assessment aims at evaluating the environmental impacts of a product or a service considering the overall life cycle.

The LCA methodology is defined by the ISO standards 14040 and 14044. Complementary to the ISO, the ILCD (International Reference Life Cycle Data System) Handbook provide a commonly accepted guidance for LCA. It consists in a set of documents that helps to harmonize and better define the LCA procedure.

LCA is meant to help policy and decision makers to decide and evaluate which could be the best solution for the analysed product/service, that can be environmentally aware while still being economically advantageous.

The LCA method can be divided in four different phases (European Commission, 2010).

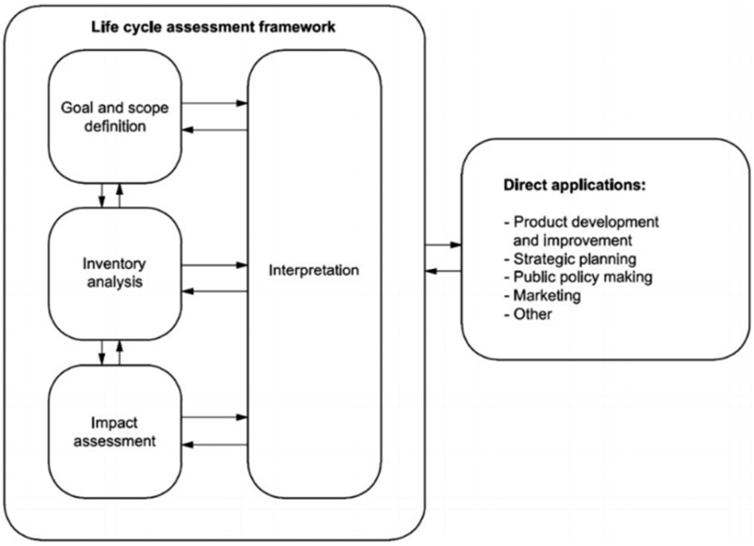


Figure 2.3. The LCA framework according to ISO 14040

1. Goal and scope definition

In the goal definition phase, at least six aspects need to be clarified:

- *Intended application(s)*

  The possible application of every LCA study can be different: comparing the environmental impacts of different products or services, evaluate the environmental impacts of a product, develop policies for the limitation of the environmental impact, etc.

  The identification of the intended application(s) for the LCA study influences the subsequent phases of the study, such as the system boundaries, the functional unit etc.
- *Reason for carrying out the study*
- *Method, assumptions and impact limitations*

  This is important to define how and when the LCA can be used and if it is representative of the specific system or if it can be used to compare the studied product or service with others.
- *Target audience*

  Defining for who the study is developed helps to choose the technical level for the report and the need of critical review.
- *Comparison, intended to be disclosed to the public*

  If the study includes a comparative assertion intended to be disclosed to the public, it need to be stated in the LCA study.
- *Committer of the study and important actors*

  The committer of the study and other important actor needs to be defined in the study.

Secondly, the object of the study needs to be identified in detail. In this context, it is important to define:

1. The function(s) of the system, functional unit and reference flow(s)

   The qualitative and quantitative function(s) of the product or service analysed must be defined in every LCA study. The qualitative definition is a description of the way the function(s) are provided, and of other qualities of the product (European Commission, 2010).

   In particular, the Functional Unit (F.U.) quantify the qualitative and quantitative aspects of the function of the system, throughout the questions:

   - What
   - How
   - How well
   - For how long

The definition of the F.U. allows to make valid comparisons between different products, as all the results will be referred to the same F.U..

The reference flow is the flow to which all other input and output flows quantitative relate. If a process has more than one reference flow (because there are more than one product), it is called a multifunctional process.

2. Definition of the system, system boundaries and completeness requirements

The "system" is defined by all the unit processes with elementary and product flows, performing one or more defined functions, that models the life cycle of the product or service analysed in the LCA study (European Commission, 2010).

The system boundaries define which part and which processes of the life cycle belong to the analysed system are required for providing its function, as defined by its F.U. They also define the boundary between the analysed system and the ecosphere and the rest of the Technosphere.

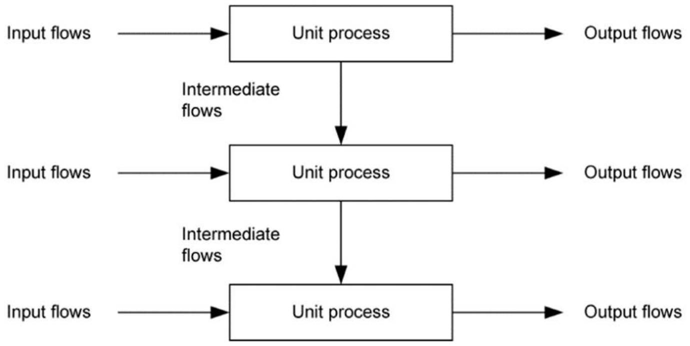
The system boundaries can be represented by a semi-schematic diagram, that shows which life cycle stages are initially considered and which not.

LCA studies are usually conducted:

- "from cradle to grave": from resource extraction (cradle) to the use phase and disposal phase (grave).
- "from cradle to gate": it is the full LCA from resource extraction to the factory gate. The use and the disposal phases are not included.

When defining the system ad system boundaries is important to specify:

- the considered unit processes. A unit process is the smallest element, considered in the LC Inventory analysis, for which input, and output data are quantified.



The unit process can be:

Black box: a unit process that includes more than one single-operation unit processes.

Single operation: a unit process that cannot be further subdivided into smallest processes.

- Elementary, intermediate and product flows, defined by ILCD Handbook as follow:
    - Elementary flow: “single substance entering the system being studied that has been drawn from the ecosphere without previous human transformation, or single substance or energy leaving the system being studied that is released into the ecosphere without subsequent human transformation” (European Commission, 2010).
    - Intermediate flow: a flow occurring between unit processes of the product system being studied
    - Product flow: a product entering from or leaving to another product system
    - Waste flow: an input flow to the waste treatment process.

Sometime, materials such as “tailings from ore mining” or “non-managed waste” are wrongly interpreted as being an elementary flow to the environment.

Data quality and cut-off criteria

Ideally, a LCA study should include all the processes that can contribute to the system. However, not all the processes are quantitatively relevant: for the less relevant ones, lower quality data could be used, reducing the effort for obtaining high quality data for those parts. Processes, activities, elementary flows that are irrelevant for the study can be entirely omitted (cut-off).

In LCA practise, cut-off criteria are used to decide the amount of material, energy or level of environmental significance that can be excluded from a study.

ILCD Handbook states that the valid cut off criteria must be defined based on the quantitative degree of completeness of the overall environmental impacts of the product system.

Data quality

During the first phase of LCA it is necessary to identify which are the data and information needed for the study and identify the required data quality.

Data quality is composed of accuracy, precision, and completeness of the inventory. Three types of representativeness need to be reached as well as possible (European Commission, 2010):

- The technological representativeness of a process/system: how well the inventory data represent the true technological characteristics described.
- The geographical representativeness: how well the inventory data represent the local situation.

- The time related representativeness: how well the inventory data represent the true age of the process or the system.

2. Life Cycle Inventory

During this phase, all the data needed are collected. The types of data are divided in primary data and secondary data.

The first ones are data that are collected from sources that are directly connected with the analysed system of the study, such as producers of goods and operator of processes and service.

Secondary data are collected from other sources, such as LCA database, scientific literature, statistics etc.)

Multifunctionality

If a process has more than one function or product (co-products) is called multifunctional.

To solve the multifunctionality, we need to associate every process to the specific product, with a process called *allocation*.

Allocation can be described as the partition of inputs and outputs of a process or a product system between the product system under study and one or more product system (*ILCD Handbook. General Guide for Life Cycle Assessment: detailed guidance, EUR24708 EN 2010*).

ISO 14044:2006 presents a hierarchy of different approaches to solve the multifunctionality problem:

1. Subdivision of multifunctional black box unit processes to mono functional single operation unit processes.
2. System expansion: expansion of the system boundaries and add for the given case missing functions and the inventories of the respective mono-functional products.
3. Substitution: solves the multifunctionality by expanding the system boundaries and substituting the not required function with an alternative way of providing it.
4. Allocation: if possible, it should be performed in accordance with the underlying causal physical relationship between the different products or functions. When it is not possible, the allocation can be performed accordingly to another relationship between the functions. It can be an economic relationship or the energy content, that is often use in the allocation between different fuels co-produced in a refinery. The disadvantage of the economic allocation is that it changes over time, as the prices of different products vary.

3. Impact assessment

The scope of this phase is to evaluate the potential environmental impacts, using the inventory data. The most relevant environmental themes (resources depletion, global impacts, regional and local impacts) are identified. Then, each inventory flow is transformed in a contribution to environmental impacts.

Modelling and evaluation of impact category can introduce subjectivity in the LCIA phase: it is very important to clearly report the assumption and choices.

The LCIA result should identify the potential environmental impacts.

The key elements of the LCIA, according to the ISO14040, are:

- Classification: assignment of emissions to impact categories according to their potential effects.

  An impact category is a class that represents the environmental theme assessed, to which the results of the inventory analysis can be assigned. Examples can be climate change, eutrophication, resource depletion, toxicity, acidification.

  During classification, the elementary flows from the inventory are assigned to the impact categories according to the substances' ability to contribute to different environmental problems. Each elementary flow can be assigned to one or more impact categories.
- Characterisation: quantification of contributions of the elementary flows to the different impact categories. In this phase, the calculation of indicator results is needed. It involves the conversion of LCI results to common units and the aggregation of the converted results within the same impact category.

  The conversation uses the *characterisation factors*. They represent the contribution from an elementary flow to an impact, for all substances which contribute to this impact. Often, the factor is expressed relative to a reference substance.

  The characterisation is done through multiplication of emission and relevant characterisation factor(s).

  The calculation of the impact on a specific category is made by summing all the flows that contribute on an impact category. Each flow is multiplied by the corresponding characterisation factor.

$$IS_i = \sum m_j * CF_{i,j}$$

Where IS_i is the impact score for the category *i*, m_j is the mass of elementary flow of the substance *j,* CF is the characterisation factor of the inventory substance j for the impact category *I.*

The characterisation factors are often obtained from values established by international Authorities based on purely scientific calculations.

According to ISO 14044, the indicator on an impact category can be chosen anywhere along the impact pathway, which links inventory data to impact on the Areas of protection (AoPs). Characterisation at the midpoint level models the impact using an indicator located somewhere along (but before the end of) the mechanism. Impact categories at the midpoint level are defined at the place where exist a common mechanism for a variety of substances within that specific impact category.

Characterisation made at the endpoint level requires modelling all the way to the impact on the entities described by the AoPs (example on Human Health, on the Natural Environment etc.).

An example of how the midpoint and endpoint categories work is described in the following scheme:

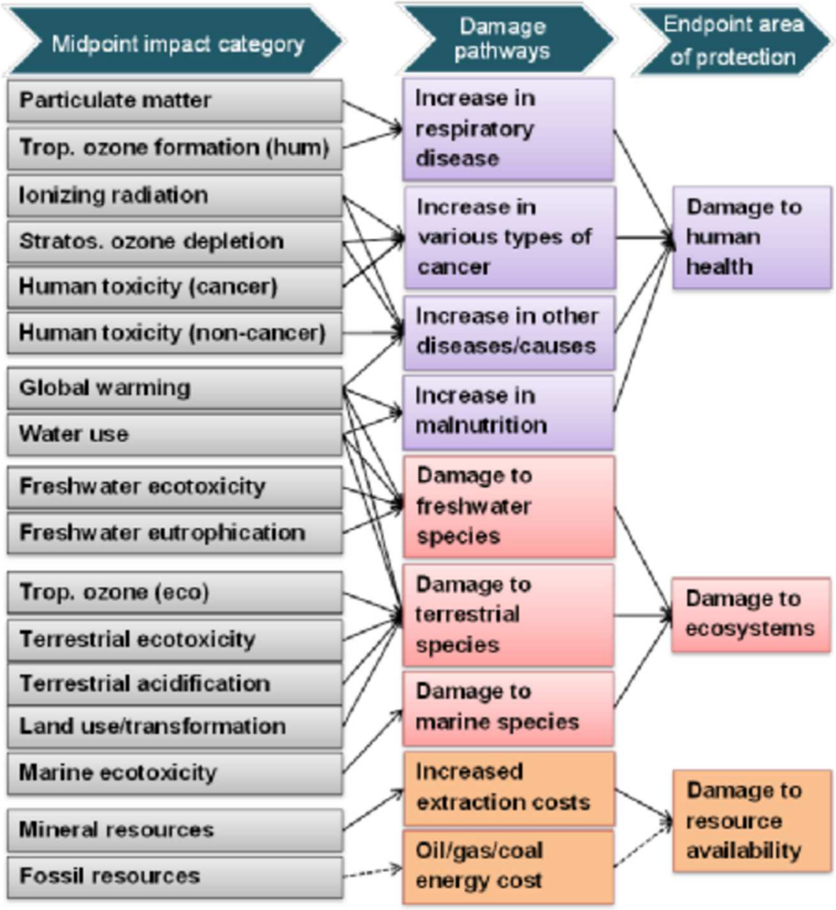


Figure 4.2 Example of the structure of Midpoind and Endpoint categories, from the ReCiPe impact assessment method.

- Normalization (optional): is the calculation of the magnitude of the category indicator results relative to some reference information (European Commission, 2010).

  The aim is to better understand the relative magnitude for each indicator results of the product system under study.

  Normalization transforms an indicator result (IS_i) by dividing it by a selected normalization factor (NF_i):

  $$NIS_i = IS_i/NF_i$$

  Where NIS_i stand for normalised impact score. Examples of reference values are:
    - the total inputs and outputs for a given area (global, regional, national or local)
    - the total inputs and outputs for a given area on a per capita basis
    - input and outputs in a baseline scenario, such as a given alternative product system.
- Weighting (optional): ranking, grouping or assignment of weights to the different impact potentials. It is the process of converting indicator results of different impact categories by using numerical factors based on value choices. Different individuals, organisations and societies may have different preferences.

  Weighting is not permitted in a comparative results assertion disclosed to the public. Weighted results should always be reported with the no weighted ones in order to maintain transparency.

4. Interpretation

This phase is a key aspect to derive robust conclusions and recommendations. It has two main purposes:

- During the iterative steps of the LCA, it serves to steer the work to improve the LCI model to meet the needs derived from the study goal.
- Serves to derive robust conclusions and recommendations.

The interpretation phase should present the results of the LCA in an understandable way. It should help the user of the study to appraise the robustness of the conclusions and understand any potential limitations of the LCI/LCA study.

Both ISO 14044 and the ILCD Handbook propose a scheme with the elements to be considered in the interpretation phase, and their relation to the other phases of the LCA study.

The elements can be grouped in:

- identification of significant issues, based on the results of the LCI and LCIA phases;
- evaluation that considers completeness, sensitivity and consistency checks;
- formulation of conclusions, limitations, and recommendations from the LCA study.

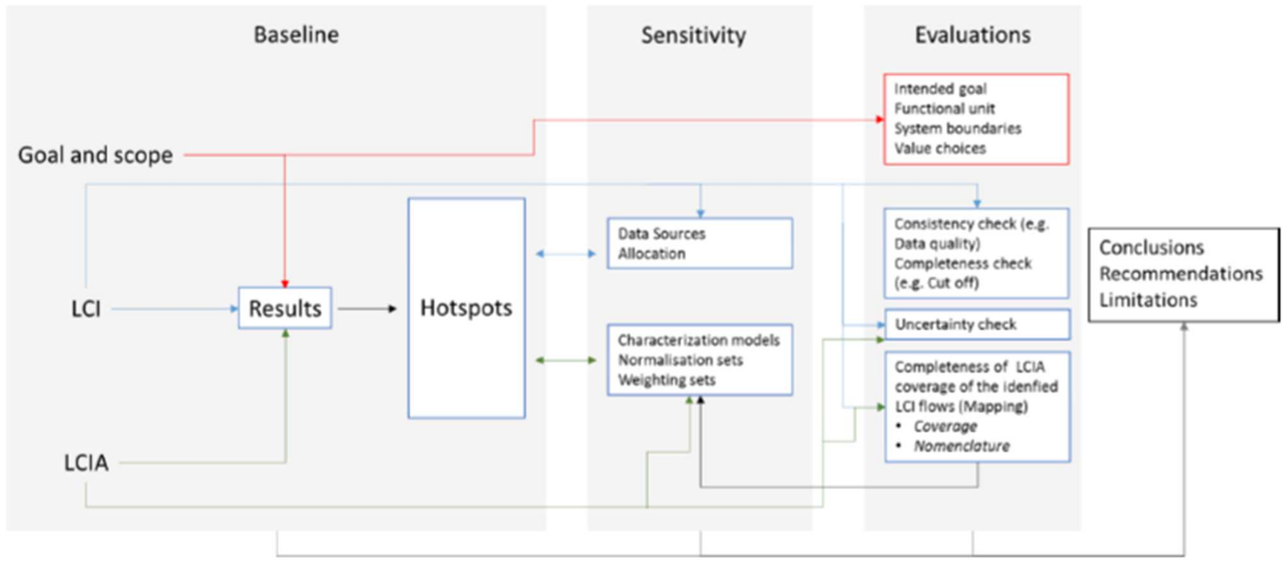


Figure 2.3. Practical application of requirements in ISO 14044 and ILCD Handbook to interpret LCI and LCIA results. [Zampori et al 2016]

Key aspects to evaluate life cycle inventories and LCIA are:

- consistency: is a qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis (assumptions, impact assessment methods, allocation criteria, data, etc.)
- completeness: is the percentage of flow that is measured or estimated. Completeness checks on the inventory are performed to determine the degree to which it is complete and whether the cut-off criteria have been met.
- sensitivity: the sensitivity check has the purpose to assess the reliability of the results and the conclusions and recommendations of the LCA study.

  It is useful to structure the sensitivity analysis along all the LCA phases. During the goal and scope definition, it is used to check for limitations in the appropriateness of the scope choices (e.g. system boundaries). During the inventory analysis it is used to check for limitations in the appropriateness of the life cycle inventory work (e.g. allocation choices, data uncertainty). Finally, in the LCIA the sensitivity analysis is to check for limitations in the appropriateness of the LCIA work (e.g. characterization method).

Any limitations of the study within the given goal and scope of the LCA study must be listed.

Recommendations based on the final conclusions of the LCA study must be logical and strictly related to the intended applications as defined in the goal of the study.

Social Life Cycle Assessment

As previously stated, Social Life Cycle Assessment aims at assessing the potential social and socio-economic impacts of product or service during the entire life cycle (SETAP, 2009).

The phase of the Social LCA are the same as the LCA: goal and scope, inventory analysis, impact assessment and interpretation.

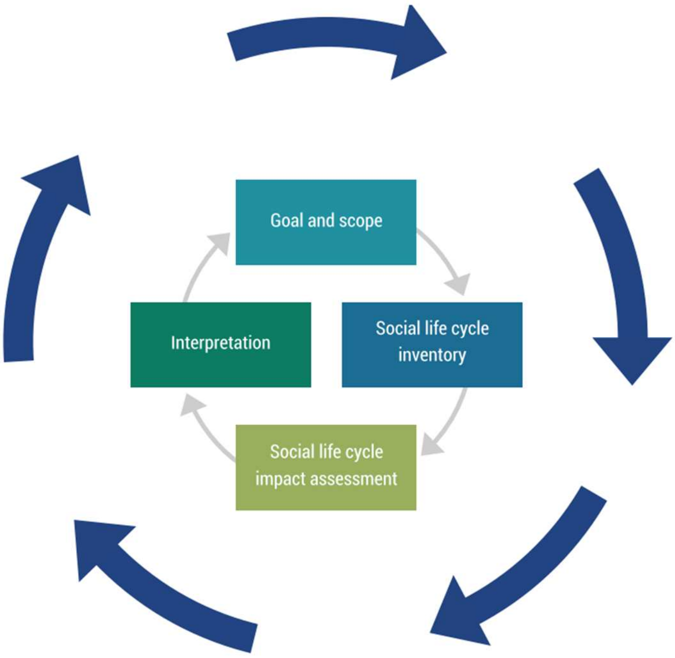


Figure 2.4.The four iterative phases of S-LCA (UNEP Setac Life Cycle Initiative, 2020)

1. Goal and scope definition

The goal of the S-LCA may vary. The purpose to conduct a S-LCA study can be to identify the main social hotspot of a product or organisation, to identify the potential social performance improvements along the life cycle, and to communicate them to the public.

During the scope definition phase, the functional unit, the reference flow, the system, and the system boundaries must be defined.

In the Social Life Cycle Assessment, the definition of the system boundaries takes place through the identification of:

- the process units to be included in the system
- all the companies and stakeholders involved and affected in the life cycle, within which the different processes take place are identified
- the companies and the links between each company involved are identified (divided into different categories of stakeholders).

In the S-LCA, therefore, the assessment of the impacts is not carried out at the process level, but at the level of companies involved in the life cycle and, more precisely, it focuses on the behaviour of the latter towards society (stakeholders) ((Walsh, 1993).

Two aspect must be taken into consideration while defining the system boundaries:

- the physical perspective, that considers the technological and economic flows in the system;
- the effect perspective based on the interaction between companies and stakeholder.

2. Inventory analysis

In this phase, the data regarding each unit process of the analysed system must be collected.

During the inventory analysis, the main interlinked processes are identified. Flow amounts are obtained for each process, and then they are quantified for the reference flow. The data that must be collected regard all the flow and processes in the analysed system.

The data collected must then be prioritized. The prioritization process can take into consideration:

- the literature review, that may highlight the main social issues not to miss during a S-LCA.
- identify the relative intensity of unit processes or activities, measured by an activity variable. Working hours is the most used activity variable, that consists in the number of worker-hours necessary to complete a production activity/unit process (UNEP Setac Life Cycle Initiative, 2020). Working hours is an activity variable that can be hard to collect, and usually it is calculated using hypothesis and estimates.
- identify the social hotspot in the product's life cycle. This can be done by a first and generic analysis using a database and a software such PSILCA (product social impact life cycle assessment), that can then be complemented with other data sources.

  Social hotspots, as defined by the Guidelines for Social Life Cycle Assessment of Products and Organizations 2020, are "unit processes located in a region (e.g. country) where a situation occurs that may be considered a problem, a risk, or an opportunity, in relation to a social issue

> that is considered to be threatening social well-being or that may contribute to its further development” (UNEP Setac Life Cycle Initiative, 2020).

Primary and site-specific data are collected by working with the organisations or by visiting in person the relevant production sites for the analysed system.

Once all the data regarding the social and socio-economical performances of the involved stakeholders are collected, the focus should be on stakeholders involved in the main processes included in the system boundaries.

The identification of all stakeholders involved in the life cycle of a product or service is a fundamental problem when performing the S-LCA. The guidelines published by UNEP in 2020 identify the following 6 main categories of stakeholders:

- Workers
- Local community
- Society (national and global)
- Consumers
- Children
- Actors of the value chain.

For each stakeholder one or more impact categories are defined, such as “working conditions” for the “workers” stakeholder category.

A subcategory is identified for each stakeholder category. A subcategory is a theme or a socially relevant attribute, such as “working hours”, “fair salary” etc. Subcategories are the basis of a S-LCA assessment because they are the items on which justification of inclusion or exclusion needs to be provided (UNEP Setac Life Cycle Initiative, 2020).

Subcategories are classified according to stakeholder and impact categories and are assessed using inventory indicators, measured by unit of measurement (or variable).

To assess each subcategory, several inventory indicators are used. Indicators are derived from the collection of data, and each one must refer to a specific subcategory (UNEP Setac Life Cycle Initiative, 2020)

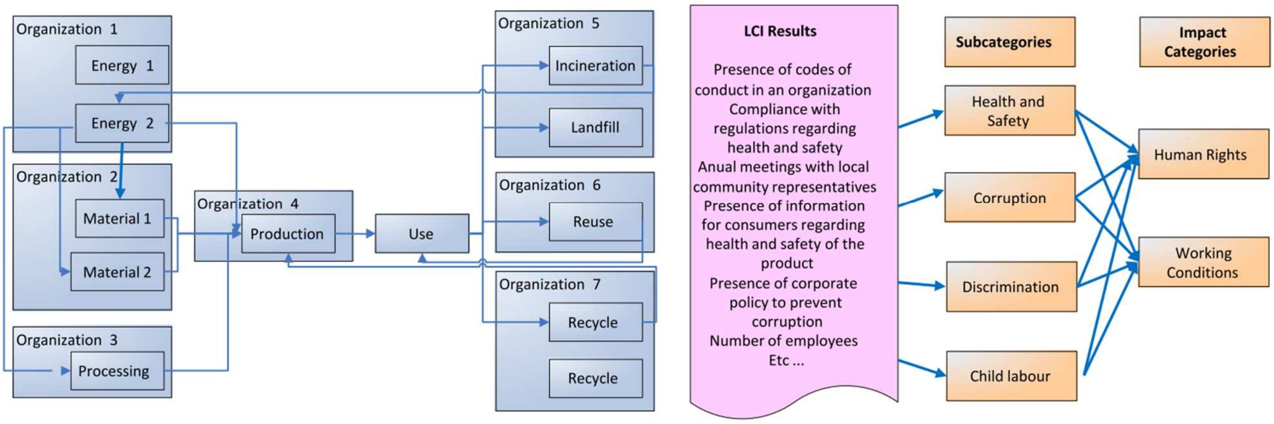
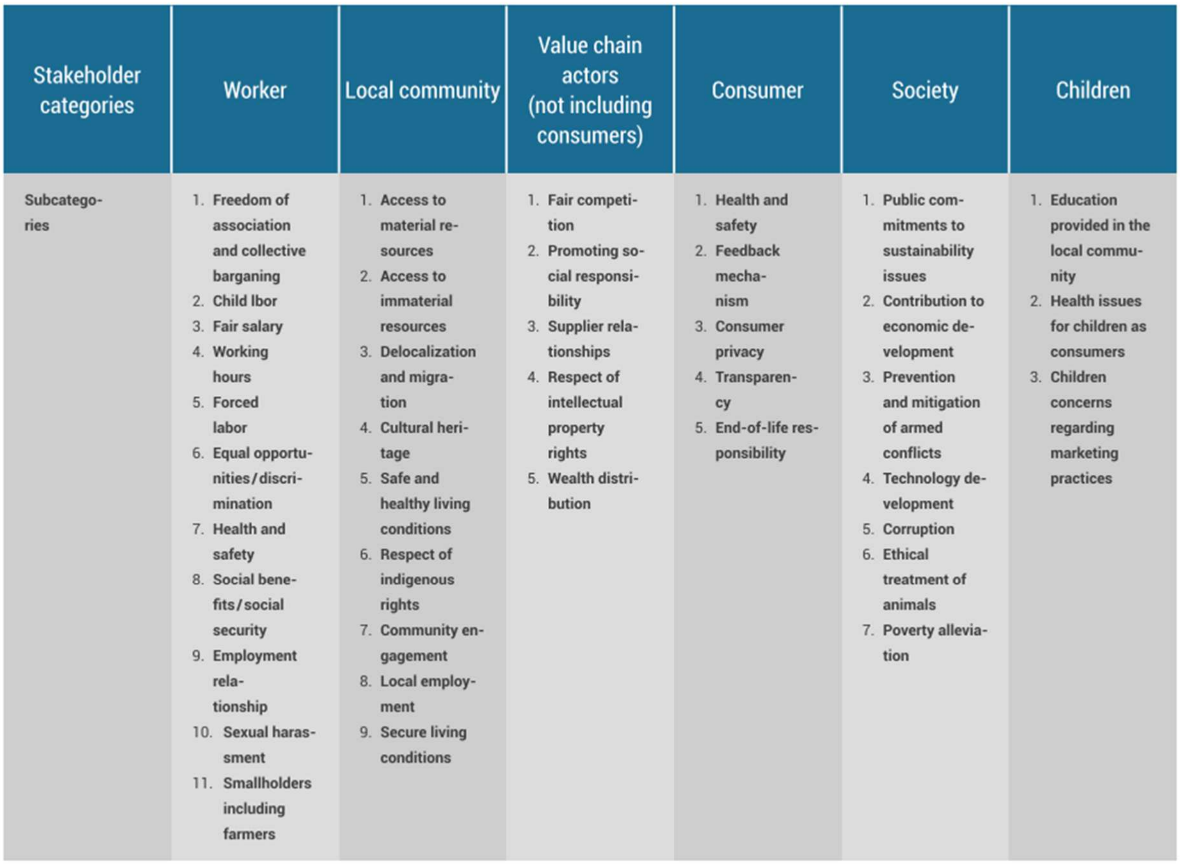


Figure 2.5. Examples of a social life cycle inventory (S-LCI) and interrelationships to subcategories and impact categories (Fan et al., 2007).



Stakeholder categories	Worker	Local community	Value chain actors (not including consumers)	Consumer	Society	Children
Subcategories	1. Freedom of association and collective barganing 2. Child lbor 3. Fair salary 4. Working hours 5. Forced labor 6. Equal opportunities/discrimination 7. Health and safety 8. Social benefits/social security 9. Employment relationship 10. Sexual harassment 11. Smallholders including farmers	1. Access to material resources 2. Access to immaterial resources 3. Delocalization and migration 4. Cultural heritage 5. Safe and healthy living conditions 6. Respect of indigenous rights 7. Community engagement 8. Local employment 9. Secure living conditions	1. Fair competition 2. Promoting social responsibility 3. Supplier relationships 4. Respect of intellectual property rights 5. Wealth distribution	1. Health and safety 2. Feedback mechanism 3. Consumer privacy 4. Transparency 5. End-of-life responsibility	1. Public commitments to sustainability issues 2. Contribution to economic development 3. Prevention and mitigation of armed conflicts 4. Technology development 5. Corruption 6. Ethical treatment of animals 7. Poverty alleviation	1. Education provided in the local community 2. Health issues for children as consumers 3. Children concerns regarding marketing practices

Figure 2.6 List of stakeholder and impact subcategories (Springer et al., 2020).

2.1 The PSILCA database

It is a database specifically developed and adapted for the needs of S-LCA.

It contains data for 19 subcategories and 65 qualitative, quantitative, and se-mi-quantitative indicators on social and environmental risks, opportunities, and positive impacts. It covers ca. 15,000 country-specific industry sectors and commodities in 189 countries based on the Eora Input/Output database.

There are two activity variables options to measure the risks/opportunities: worker-hours and value added. For every data point, information on data quality is provide and can be calculated for the entire product system (Maister et al., 2020).

3. Impacts assessment

This phase aims at "calculating, understanding and evaluating the magnitude and significance of the potential social impacts of a product system throughout the life cycle of the product" (UNEP Setac Life Cycle Initiative, 2020).

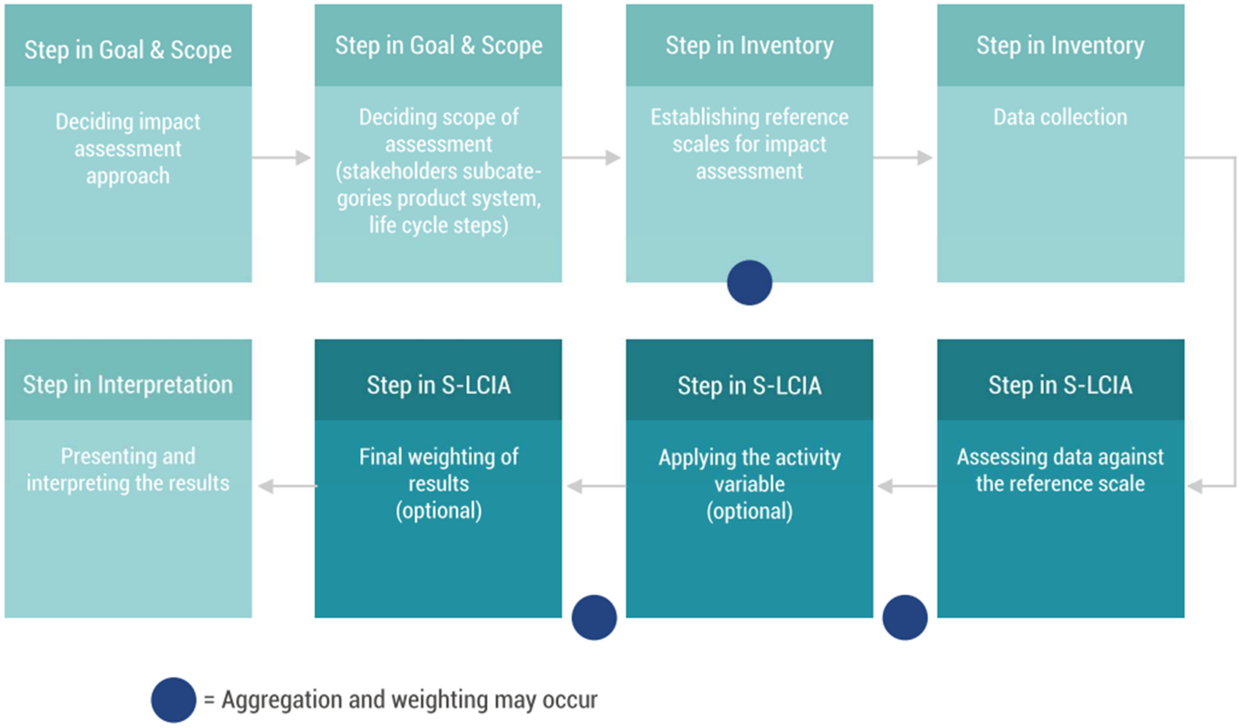


Figure 2.7 Steps related to the impact assessment process for the Reference scale approach (UNEP Setac Life Cycle Initiative, 2020)

The databases for S-LCA such PSILCA automatize a great number of steps, using international and national data from organizations.

The following steps from Figure 4 are all performed during an S-LCA database analysis:

- Establish reference scales for impact assessment; the databases have a set of pre-determined reference scales for each impact subcategory in their framework;
- Data collection: the software collects data for the specific case, drawing on generic data from pre-selected databases or other data sources;
- Assessing data against the reference scale: the databases proceed to assess the data collected against the pre-determined reference scales;
- Applying an impact assessment method to group by subcategory or impact category and aggregate results over the value chain using an activity variable;

- Final weighting of results; the databases either apply weighting or give users the opportunity to apply the weighting onto the results;
- Presenting the results. The databases provide some infographics to present the results. It is also possible to use the raw data to develop their own infographics for Interpretation (UNEP Setac Life Cycle Initiative, 2020).

4. Interpretation

The interpretation phase must be done during all the S-LCA process and it includes:

- Completeness check;
- Consistency check;
- Sensitivity and data quality check;
- Materiality assessment;
- Conclusions, limitations, and recommendations.

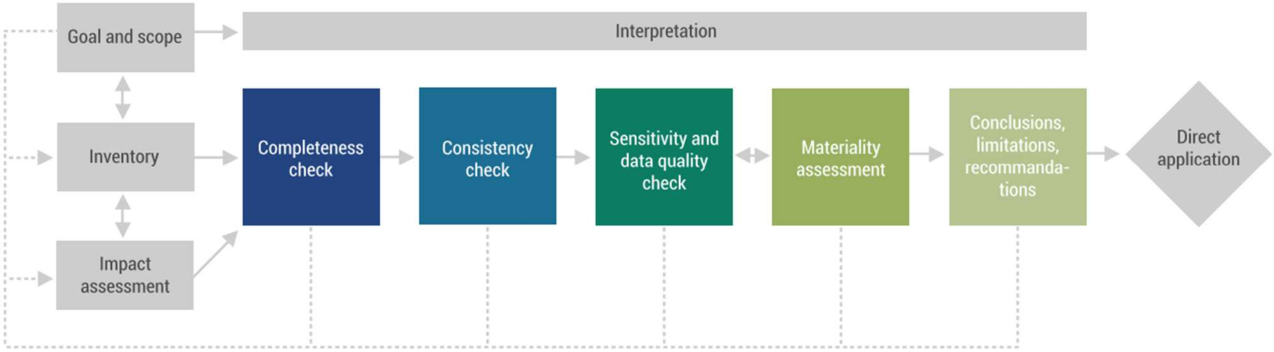


Figure 2.8. The interpretation phase and the relation with the other phases of S-LCA (UNEP Setac Life Cycle Initiative, 2020).

The interpretations phase steps are conducted similarly to the LCA approach.

Life Cycle Costing

Life cycle costing, or LCC, is a compilation and assessment of all costs related to a product, over its entire life cycle, from production to use, maintenance and disposal.

In the Code of practice for Life Cycle Costing, the method is described as “a powerful technique that supports the analytical processes by which managers can make the most cost-effective decisions on options presented to them at differing life cycle stages and at different levels of the life cycle cost estimate” (Research and Technology Organisation of NATO, 2007).

LCC has the same basic approach as the Life Cycle Assessment, with some variations depending on the level of details.

Define the aim and objectives

Define the costing boundaries

The definition of the costing boundaries is necessary to identify which costs must be included in the study. In LCC, three different costing boundaries must be defined:

- The first, is related to the definition of the system boundaries.
- The second needs to establish the time boundaries, which program phase must be taken into consideration etc;
- The third defines what will be included in the scope of the study (Research and Technology Organisation of NATO, 2007).

Develop the Structure of the Life Cycle Cost Framework

The costing framework should consider the immediate needs of the current phase and has to be adaptable to the developing needs of later phases.

A typical outline is showed in the following figure:

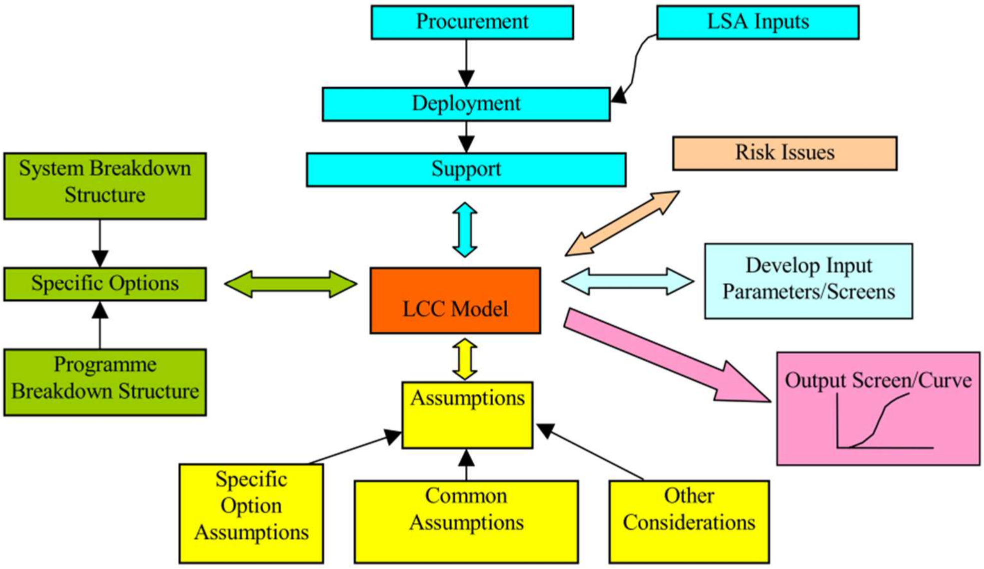


Figure 2.9. Example of a Typical Life Cycle Cost Framework Structure (Research and Technology Organisation of NATO, 2007).

The figure shows the framework broken down into several areas:

- On the left (in green) would be the cost breakdown structure reflecting the system, any specific options relating to the system and details of the programme timescale.
- On the top (in blue) would be the programme documentation relating to procurement strategy, how the system will be deployed in operational and peacetime use and how it will be supported in these environments.

- The ILS (Integrated Logistic Support) and the LSA (Logistic Support Analysis) inputs would support the understanding of the proposed deployment.
- At the bottom (in yellow) would be the ground rules and assumptions.
- On the right-hand side, the risk issues could be included within the model to obtain a ‘risk adjusted’ cost (Research and Technology Organisation of NATO, 2007).

Inventory analysis

Once the costing framework structure is set, the subsequential step is to collect the data regarding the cost elements (cost breakdown structure). Usual methods to gather the data needed are:

- Industrial visits will produce information and data on the product
- Market survey, good for gathering technical data, but limited in obtaining prices, because are likely to have a large margin of error.
- Data for direct use within the study: actual equipment procurement costs, published data for equipment and services, etc.
- Data on analogous systems
- Data from logistic analysis information and data from ILS (Integrated Logistic Support) studies to provide data on component reliability, maintainability and supply chain information (Research and Technology Organisation of NATO, 2007).

Cost analysis

The level of analysis required within the study varies. In some cases, simple accountancy calculations involving discounted cash flow may be sufficient.

Cost analysis usually include the testing of parameters and assumptions by means of sensitivity analysis. Testing of alternative assumptions should also be conducted. It is essential that any life cycle cost model can support these types of analyses so that the decision-makers have a full understanding of the costs and the financial implications.

Presentation of the results

The results of cost studies can be presented in a wide range of tabular and graphical forms.

The LCC results should be summarised and discussed with the stakeholders, along with the underlying assumptions, to assure that the life cycle cost fully meets the stakeholders’ needs.

Mine tailings

As previously stated, the increasing need for new carbon neutral technologies has prompt the demand for the extraction of metals, such as Zn, Cu, Ni, Co, and rare earth metals.

The extraction of these resources comes with the production of a significant volume of waste materials, at a rate of several thousand million tonnes per year (Kossoff et al., 2014).

Figure 5. Mine tailings dam failure , Brazil (mining-technology.com)

These materials are called mine "tailings", to describe the by-products of different extractive industries, such as those for aluminium, coal, precious and base metals. Mine tailings are described as "mixtures of crushed rock and processing fluids from mills, washeries or concentrators that remain after the extraction of economic metals, minerals, mineral fuels or coal from the mine resource" (Kossoff et al., 2014). They represent the uneconomic and usually unrecoverable fraction of the mineral extraction (Dixon-Hardy & Engels, 2007).

Usually, tailings are stored in mine dumps, close to the mining activity.

The chemical composition of mine tailings depends on different factors, such as:

- the mineralogy of the ore body
- the processing fluids used
- the type and the efficiency of extraction (Kossoff et al., 2014).

Tailings can be divided in three different phases:

- the gangue fraction, usually dominated by quartz (SiO_2).
- the sulphide fraction mostly composed by pyrite (FeS_2), pyrrhotite ($Fe_{1-n}S$), where n ranges from 0-0.2) and arsenopyrite (FeAsS).
- the secondary mineral fraction, composed by different oxide and sulphides, depending on the chemical composition of the original ores.

Storage techniques

Historically, mine tailings were usually discharged into the closest rivers, oceans and lakes (Adiansyah et al., 2015; Dixon-Hardy & Engels, 2007), a process called direct disposal.

Specifically, direct disposal can be divided in riverine tailings disposal (RTD) and submarine tailings disposal (STD).

RTD occurs when the tailings are discharged by a pipe directly into the river. This type of disposal is no longer applied, due to the severe environmental problems that it causes (Adiansyah et al., 2015). STD uses pipes to discharge tailings at a certain depth into the oceans. In this way, the tailings cannot contaminate the surface of the oceans and interact with the abiotic and biotic system. STD is used especially in the Western Pacific region, where other on-shore technique are not feasible, due to high seismic activities, high rainfall or land availability (Dixon-Hardy & Engels, 2007). This type of disposal is now used by several mining companies. It is considered safe if some requirements are fulfilled: the discharge point must be under the thermocline layer and the euphotic zone, and the tailings must not leach contaminant at the mixing point. Also, the oxygen level in those zones is minimal, avoiding the dissolution and mobilization of contaminants. However, there is the risk of leakage from the pipe that could cause environmental problems for the benthic organisms population, especially for the metal concentration in the marine environment and the increased turbidity of the water column (Adiansyah et al., 2015; Dixon-Hardy & Engels, 2007).

To reduce the risk of environmental liabilities and the costs for remediation, different storage methods for mine tailings have been developed. Mine tailings are now usually stored into a dam, a cell, or impoundment (Adiansyah et al., 2015; Jakubick, 2000). This type of storage is called indirect disposal.

Some examples of this strategy are:

- Conventional impoundment: it is a surface structure, designed to retain mine tailings and water. The aim is to reclaim the water for use in the processing plant as required (Dixon-Hardy & Engels, 2007).
- Thickened tailings: tailings are dewatered to the point where they form a homogeneous mass when deposited from the end of a pipe.
- In-pit tailings storage is the process of backfilling abandoned open-pit surface mines with mine tailings. This type of storage can be very convenient for a mine operator. In fact, it allows to avoid the costs of design, construction, and operation of a conventional or thickened facility (Dixon-Hardy & Engels, 2007).

The storage of mine tailings represents a long-term engineering and environmental challenge. The failings on the system used to store mine tailings occasionally cause catastrophic environmental pollution (Falagán et al., 2017).

The environmental impacts

The unsafe storage of mine tailings, together with the extraction of metals, can lead to severe chain environmental problems, such as the acid mine drainage.

Acid mine drainage

Both the extraction and the leaching of metals from mine tailings can cause serious damages to the areas surrounding the mine site. In particular, surface and ground waters are affected by the acidification and sedimentation of heavy and toxic metals (Harding & Boothroyd, 2004).

This phenomenon is called acid mine drainage (AMD) and can cause different damages, that can be classified in physical, chemical, biological and ecological (Gray, 1997).

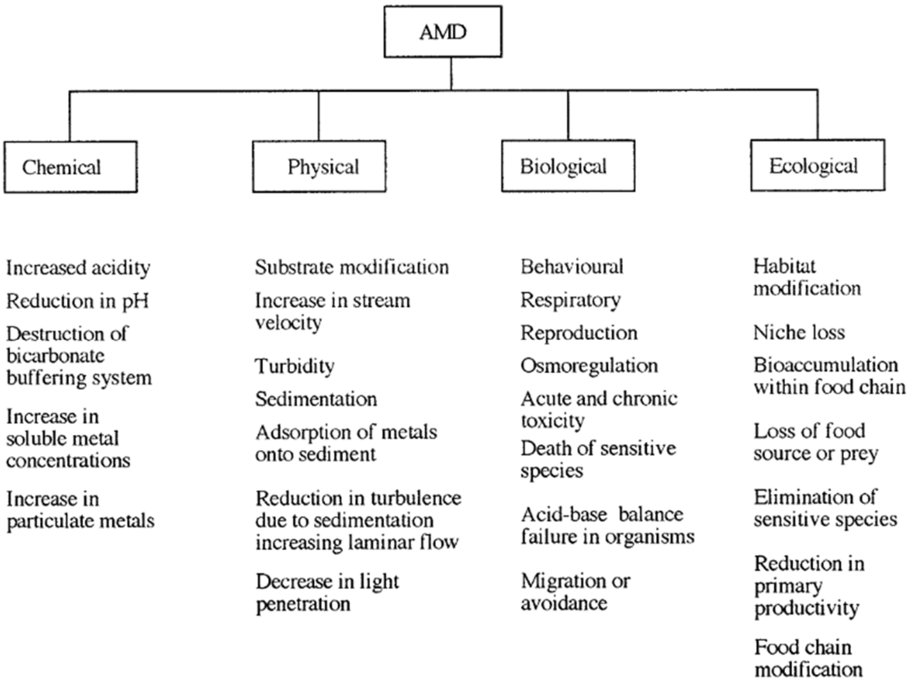


Figure 3.2 Acid mine drainage effects (Gray, 1997).

Acid mine drainage (AMD) is cited as one of the most important impacts of mining activities, that can occur especially after the closure of the mine site (Rezaie & Anderson, 2020). In fact, with the stop of the operations and the pumping, water can flow into the retired mine.

When the ores contains big amounts of pyrite (mainly composed by sulphates) then exposed to oxygen and water, several reaction can occur (Akcil & Koldas, 2006; Harding & Boothroyd, 2004), resulting in the acidification of waters:

1) $FeS_2 + 7/20_2 + H_20 = Fe^{2+} + 2S0_4^{2+} + 2H^+$

2) $Fe^{2+} + 1/4\ 0_2 + H^+ = Fe^{3+} + 1/2H_20$

3) $Fe^{3+} + 3H_20 = Fe\ (OH)_2 + 3H^+$

4) $FeS_2 + 14Fe^{3+} + H_20 = 12Fe^{2+} + 2S0_4{}^{2+} + 16H^+$

Beside pyrite, other minerals can contribute to AMD, like arsenopyrite, pyrrhotite, sphalerite. Bacteria that occur naturally in the ores can accelerate AMD, by breaking down sulphide minerals (Akcil & Koldas, 2006).

The acidification of water streams eventually leads to chain effects, ending with the collapse of the biological structure due to the elimination of animal and vegetal species and the reduction of the food supply chain (Gray, 1997). The metal sedimentation in the long-term period causes the bioaccumulation of heavy metals in the flora and fauna.

The impact, however, can be partially controlled by the buffering capacity of the water streams (Gray, 1997). The hard buffered water systems are less likely to be heavily affected by acid drain damage, while major impacts can occur during the sedimentation of dangerous metals.

The primary factors that can lead to acid mine drainage can be (Akcil & Koldas, 2006):

- pH;
- temperature;
- oxygen content of water streams and ores/tailings;
- area of exposure of sulphates;
- bacterial activities.

AMD effects may vary a lot depending on the nature of ores and tailings. Oxidants different form oxygen can intervene, and the specific nature of sulphides minerals can lead to different pathways that are difficult to predict (Akcil & Koldas, 2006).

The management options

Usually, once the AMD is started, different remediation techniques can be applied (Park et al., 2019). Some of these options are neutralisation, adsorption, ion exchange, biological mediation.

Conventionally, AMD are treated with neutralization of the acids, by adding alkaline compound like limestone, lime, sodium carbonate and magnesia, allowing the precipitation of heavy metals and hydroxides (Akcil & Koldas, 2006; Rezaie & Anderson, 2020). These compounds can then be flocculated, forming a high dense sludge (Akcil & Koldas, 2006), that can be then discharged to rivers. Neutralisation of tailings allows to control redox reactions of sulphides and the biological activities, by increasing the pH to 7-8. However, this option does not work if the AMD pH is lower than 2; moreover, increasing the pH level only to 7.5-8 does not allow the removal of some toxic metals such as Mn (Park et al., 2019).

These types of treatment requires huge investment, due to the big amounts of reagents required, operation and maintenance costs, and disposal of sludges.

Instead of focusing on AMD remediation, many studies propose different prevention techniques, by excluding the contact with the components that drive the acid drainage: oxygen, water, and microorganisms.

An example is the oxygen barrier, used to limit the O_2 availability to sulphide mine tailings, through dry covers and subacqueous disposal (water cover) (Park et al., 2019). The main feature is the avoided contact between the tailings and the water and oxygen, thanks to the covers composed of fine-grained materials, industrial alkaline wastes (Bellaloui et al., 1999)or low sulphide tailings (Bussière et al., 2004).

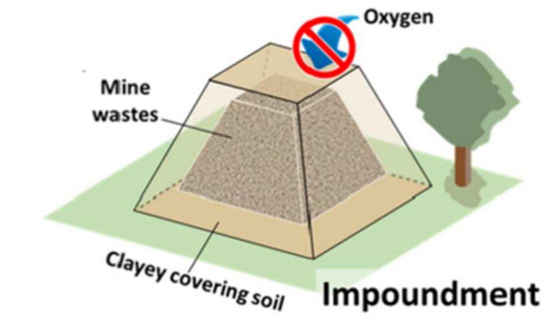


Figure 3.3 Schematic diagram of impoundment (oxigen barrier) (Park et al., 2019)

Another valuable option is the blending of sulphide tailing with basic materials, like lime, limestone, and phosphate minerals. They immobilize soluble metals and metalloids via precipitation, thanks to the consumption of H^+ produced by sulfidic tailings (Hakkou et al., 2009). Finding the stoichiometric balance between acid production and acid consumption is fundamental to neutralise the tailings, therefore maximizing the efficiency of the operation (Park et al., 2019).

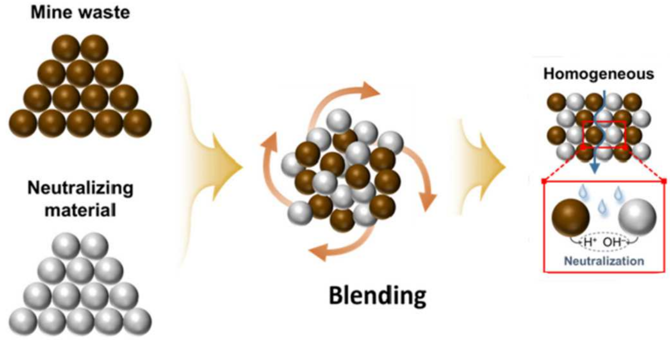


Figure 6.4 Schematic diagram of mine wastes with neutralizing materials (Park et al., 2019)

Prevention techniques do not need continuous treatment and maintenance. For this reason, they are more sustainable than remediation techniques. Nevertheless, they are still under development and are focused mostly on pure pyrite system (Park et al., 2019).

Another option to minimise the acid mine drainage effect is the recycling of mine tailings as construction material. The potential benefits can be many, such as the reduction of the tailings volume and the replacement of traditional construction material that can be expensive.

Bioleaching process of metals recycling

Mine tailings, despite the adverse environmental impacts, may also represent an opportunity, thanks to the presence of valuable and critical metals (Mäkinen et al., 2020). For this reason, there have been different proposal of new technologies for the cost-efficient recovery of tailings for metal extraction.

Conventional metal extraction methods, such as hydrometallurgy and pyrometallurgy, are not economically convenient for the extraction from low-grade ores body (Sajjad et al., 2019). Moreover, such techniques cause air, soil, and water pollution.

In the view of a more sustainable mining, the methods used to recover metals for mine tailings have to be less energy and economically demanding, while being also environmentally friendly.

Different treatment technologies have been suggested, also in combination: flotation, magnetic separation, pyrometallurgical treatment (Mäkinen et al., 2020). The aim of these processes is to transform the minerals from a reactive to a stable form.

In this context, the bioleaching process can be a relatively economically available option. It is a bio hydrometallurgical approach, consisting in the extraction of metals from sulphides or iron containing ores, thanks to microorganisms. The activity of these organisms (in particular acidophilic chemolithotrophic microorganisms) is used to convert insoluble compound into soluble ones, that can later be recovered (Sajjad et al., 2019; Ye et al., 2017). Microorganisms in fact can use sulphur or Fe^{2+} as a source of energy, allowing the dissolution of metallic sulphides that can be extracted (Ye et al., 2017).

Bioleaching is a slower technique compared to the chemical leaching, but it allows the reduction of toxic chemicals and of the capital costs (Mäkinen et al., 2020).

Different studies investigate the use of bioleaching process to extract valuable metals from mine slags or tailings (Falagán et al., 2017; Hubau et al., 2020; Mäkinen et al., 2020; Sajjad et al., 2019; Ye et al., 2017).

From these studies it emerged that the characterisation of mine tailings is fundamental to design a bioleaching plant that allows the economically feasible and convenient extraction of metals. The identification of the main minerals in the mine tailings allows to understand which is the most economically convenient metal to extract.

In addition, the accurate selection of bioleaching parameter such as pH, temperature, and concentration of the ore in the bioleaching tank influences the efficiency of the metal extraction, and the profitability of the process.

Different studies show the efficient extraction of valuable metals through the bioleaching technology. Falagàn et.al (2017) achieved more than 90% of copper extraction from mine tailings, and more than 75% of zinc was leached from Tres Marias Brazil zinc plant leach residues (Sethurajan et al., 2017). Under optimum conditions, Ghassa et al. extracted 98.5% zinc and 98% of cadmium (Ghassa et al., 2014).

Bioleaching can achieve great extraction rates; therefore, it can be a valuable technique for the extraction of metals from low-grade ores, that could not be mined otherwise. In recent years, different pilot plants have been designed, to implement this technique and make it feasible in the next future.

The case study

Most of the easily accessible metal resources in Europe are exhausted (Hubau et al., 2020). This leads the European Union (EU) Member States to depend on other States for the procurement of metals.

For this reason, the European commission (EC) supports several projects, which focus on the reprocessing of mine tailings. In fact, these materials can be a source of valuable metals and useful materials for the building and construction sector.

The benefits derived from the reprocessing of mine tailings are, among others:

- Reduction of environmental impacts
- Economic profitability
- Development of new and efficient processes that may allow to extract metals and critical elements (Hubau et al., 2020).

The NEMO project

This study is placed in the context of the H2020 NEMO (Near zero-waste recycling of low-grade sulphidic mining waste for critical-metal, mineral and construction raw-material production in a circular economy) project. NEMO aims to implement new technologies for the recovery of valuable and critical metals (Cu, Pb, Zn, Ni, Co, Mn, Mg and rare earth elements) from sulphidic mine residues. Once the metals are extracted from the sulphidic mine residues, the near-zero waste strategy will be achieved by recycling the residual fraction as a substitute for cement or aggregates for the construction industry (Nemo, 2018).

One of NEMO's goal is to assess the sustainability of the proposed technologies, from the environmental, social, and economic point of view.

Since NEMO's data were not available, this thesis uses a similar project as case study and data source: the Mondo Minerals nickel sulphide bioleaching project.

The Mondo Minerals project aim is to extract valuable metals from the sulphide tailings produced as a by-product in two mining sites in Finland: Sotkamo and Vuonos.

The sulphide concentrate from the talc mining operations in Sotkamo and Vuonos contains pyrrhotite, pentlandite, pyrite, gersdorffite, and magnesite (Neale et al., 2015). Valuable amount of nickel and smaller amounts of arsenic and cobalt can be extracted from this concentrate, avoiding environmental liabilities.

The best solution for the valorisation of the tailings came from the Mintek bioleaching technology, that provided the design criteria for the bioleaching plant. All the data and the processes' description are taken from the Mondo Minerals report by Neale et.al (2015).

The main treatment processes are the bioleaching of the sulphide concentrate followed by an iron and arsenic removal process. The plant requires to treat 35 t/d of sulphide concentrate with a targeted nickel recover of 93%. The final product is a nickel and cobalt concentrate.

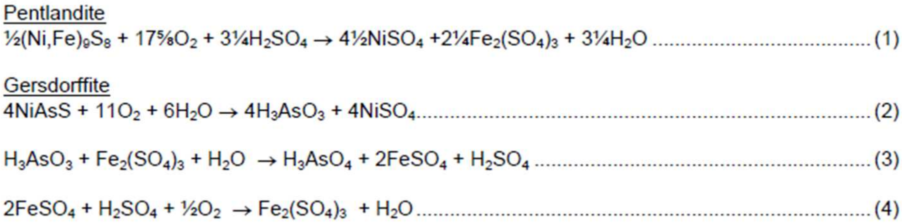
Process flowsheets and description

The nickel leaching plant aims at the recovery of a mixed hydroxide precipitate (MHP) composed by 42% of nickel and 2.4 % of cobalt that can be sold as secondary metals. The process allows to also extract iron arsenate, which is suitable for impounding. The final neutralized tailings can be dammed in the Vuonos tailings dam.

The plant consists of different sequential steps.

1. Regrinding. The sulphate concentrate needs to be grinded at P_{80}. The reduction of the grain size help to improve the nickel bioleach.
2. Magnetic separation. Some of the pyrrhotite present in this phase is rejected in the sulphate tailings.
3. Flotation. The aim is to upgrade and eliminate from the concentrate the non-magnetic fraction, therefore removing magnesite and talc. The removal of the magnesite is necessary because its presence in the bioleaching tank would require bigger amounts of acid to maintain the pH range in the reactors.
4. Bioleaching. The bioleaching process is conducted in a circuit of 7 tanks, with a residence time of 7 days. The primary oxidation phase is conducted in the first three tanks (reactors) that operate in parallel, where the concentrate is fed. The secondary oxidation phase occurs in the other four tanks, operating in series.

   The main reaction occurring in the tanks are:



Pentlandite

$$\tfrac{1}{2}(Ni,Fe)_9S_8 + 17\tfrac{5}{8}O_2 + 3\tfrac{1}{4}H_2SO_4 \rightarrow 4\tfrac{1}{2}NiSO_4 + 2\tfrac{1}{4}Fe_2(SO_4)_3 + 3\tfrac{1}{4}H_2O \quad (1)$$

Gersdorffite

$$4NiAsS + 11O_2 + 6H_2O \rightarrow 4H_3AsO_3 + 4NiSO_4 \quad (2)$$

$$H_3AsO_3 + Fe_2(SO_4)_3 + H_2O \rightarrow H_3AsO_4 + 2FeSO_4 + H_2SO_4 \quad (3)$$

$$2FeSO_4 + H_2SO_4 + \tfrac{1}{2}O_2 \rightarrow Fe_2(SO_4)_3 + H_2O \quad (4)$$

Figure 4.7 Chemical reaction occurring in the bioleaching tanks (Neale et al., 2015b)

Pyrrhotite

$$Fe_7S_8 + 7Fe_2(SO_4)_3 \rightarrow 21FeSO_4 + 8S \tag{5}$$

$$2FeSO_4 + H_2SO_4 + \tfrac{1}{2}O_2 \rightarrow Fe_2(SO_4)_3 + H_2O \tag{6}$$

$$S + H_2O + 1\tfrac{1}{2}O_2 \rightarrow H_2SO_4 \tag{7}$$

Pyrite

$$FeS_2 + {}^{15}/_{4}O_2 + \tfrac{1}{2}H_2O \rightarrow \tfrac{1}{2}Fe_2(SO_4)_3 + \tfrac{1}{2}H_2SO_4 \tag{8}$$

Figure 4.8 Chemical reaction occurring in the in the bioleaching tanks (Neale et al., 2015)

The circuit requires the addition of CO_2 gas, to feed the bacteria with enough carbon for their growth. This is necessary for the removal of magnesite from the magnetic separation phase.

5. Iron and arsenic removal. In this phase, iron and arsenic are removed from the slurry received by the bioleaching phase. The addition of limestone allows the precipitation of ferric arsenate ($FeAsO_4$). The solids are then separated from the solution, which goes to the metal precipitation tank.

   The main reaction that occur in the tank are:

$$2FeSO_4 + H_2SO_4 + \tfrac{1}{2}O_2 \rightarrow Fe_2(SO_4)_3 + H_2O \tag{9}$$

$$FeSO_4 + 2H_2O \rightarrow Fe(OH)_2 + H_2SO_4 \tag{10}$$

$$Fe_2(SO_4)_3 + 2H_3AsO_4 \rightarrow 2FeAsO_4 + 3H_2SO_4 \tag{11}$$

$$Al_2(SO_4)_3 + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2SO_4 \tag{12}$$

$$H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + H_2O + CO_2 \tag{13}$$

$$CaSO_4 + 2H_2O \rightarrow CaSO_4.2H_2O \tag{14}$$

Figure 4.9 Chemical reaction occurring in the and arsenic removal circuit (Neale et al., 2015)

6. Metal precipitation. In this phase, a mixed nickel and cobalt hydroxide product (MHP) is precipitated, thanks to the addition of MgO in the tanks. The MHP is composed approximately by 42% of Ni and 2.4% of Co (M Gericke, C Pawlik, DW Dew, P van Aswegen, SCC Barnett, 2015) and is suitable for sale.

   The main reaction that occur are:

$$MgO + H_2O \rightarrow Mg(OH)_2 \tag{15}$$

$$5NiSO_4 + 4Mg(OH)_2 \rightarrow 4MgSO_4 + Ni_5(OH)_8SO_4 \tag{16}$$

$$CoSO_4 + Mg(OH)_2 \rightarrow Co(OH)_2 + MgSO_4 \tag{17}$$

Figure 10.4 Chemical reaction occurring in the metal precipitation tank

7. Recycle water treatment. The neutralised water from the metal precipitation phase is used as process water for the bioleaching plant. However, the water has a high grade of MgO, hence, it must be removed with the addition of lime. The precipitated gypsum and hydroxide

are then removed. The resulting material is the neutralised in the tailing neutralisation phase.

8. Tailings neutralization. The aim of this phase is to neutralise any residual metal before the discharge of the tailings to the tailings dam. The tank collect the tailings from the iron and arsenic removal and the recycle water treatment phases. The tailings are treated with limestone and lime and then they are discharged in the existing tailings dam.

$$MSO_4 + Ca(OH)_2 \rightarrow M(OH)_2 + CaSO_4 \ldots\ldots\ldots\ldots (18)$$

Figure 4.11 Chemical reaction occurring in the tailings neutralisation tank

The environmental, economic, and social benefits and impacts of this project will be accessed using LCA, LCC, and S-LCA.

Life Cycle Assessment, Life Cycle Costing and Social Life Cycle Assessment

Goals and scope definition

The goal of the LCA in this study is to provide an environmental analysis of the recovery of nickel and cobalt thanks to the Mondo Minerals' project. The results will identify the environmental benefits and costs of the project.

Accordingly, the LCC goal is to assess the financial feasibility of the project, hence, to evaluate the cost-effectiveness of the metal recovery from the Vuonos and Sotkamo mine tailings.

S-LCA aims to provide a project's preliminary social impact assessment, to pinpoint the main social implication of the metal recovery through the Mondo Minerals bioleaching project.

Definition of functional unit, system, and system boundaries

The definition of the functional unit (F.U.) is fundamental because it defines the reference to the mass and energy (for the LCA) and cost (for the LCC) flows calculated during the analysis. In this study, F.U. refers to one year of nickel and cobalt concentrate production.

System boundaries

The definition of system boundaries is necessary to set the processes that must be included in the analysis. This means that any other process is not included in the environmental, economic, and social analysis. Hence, the impacts of these processes are not calculated.

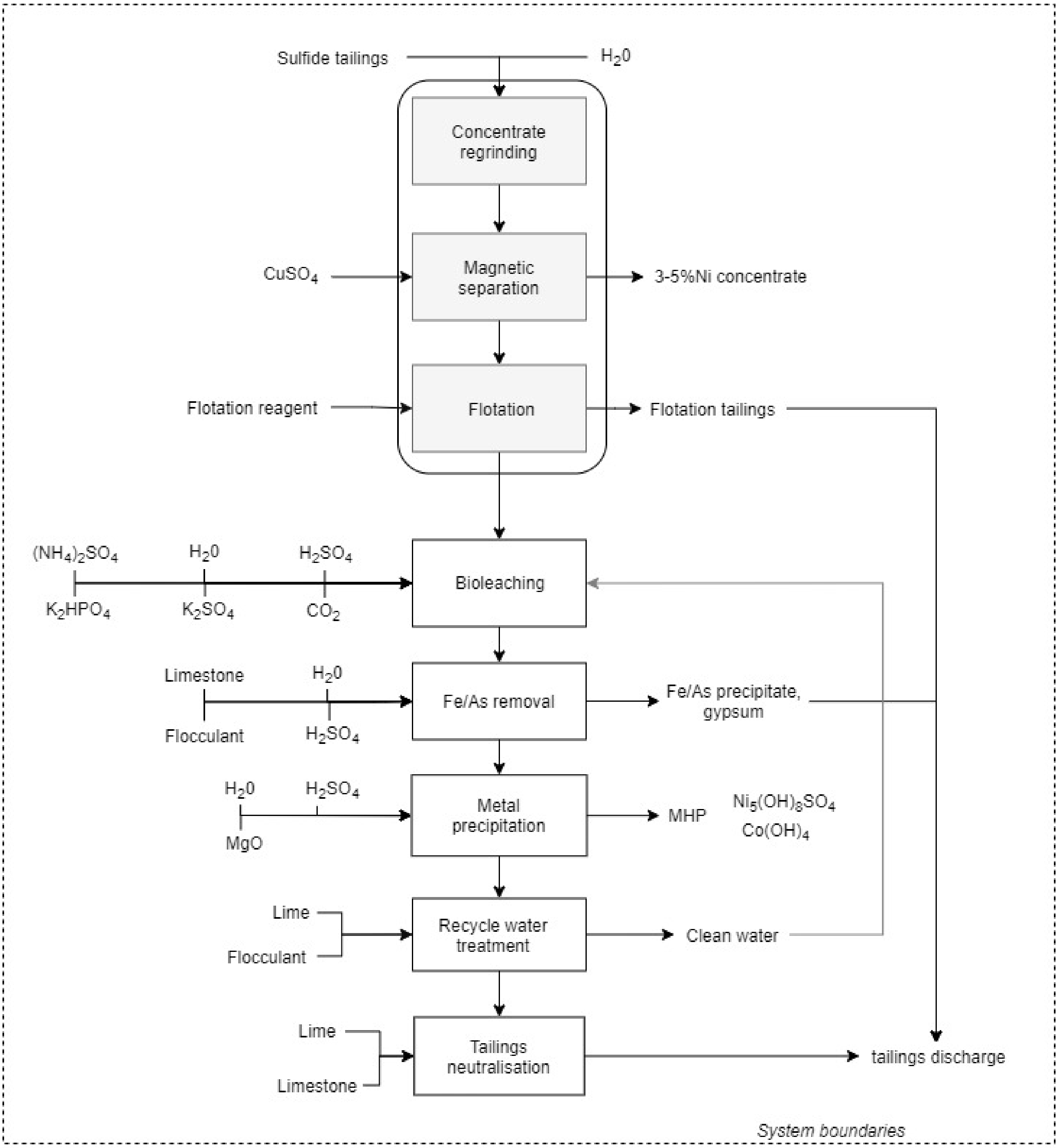


Figure 4.12. Analysed system and system boundaries

LC Inventory

In the Life Cycle Inventory phase, the consumption and the quantity of mass flows and energy flows are estimated. The inputs and outputs flows are always referred to the functional unit.

The data listed are collected from the Mondo Mineral nickel bioleaching project article (Neale et al., 2015). When not mentioned, the mass and energy data were estimated stoichiometrically.

Limitation of the study

When possible, the data were collected from literature or calculated stoichiometrically.

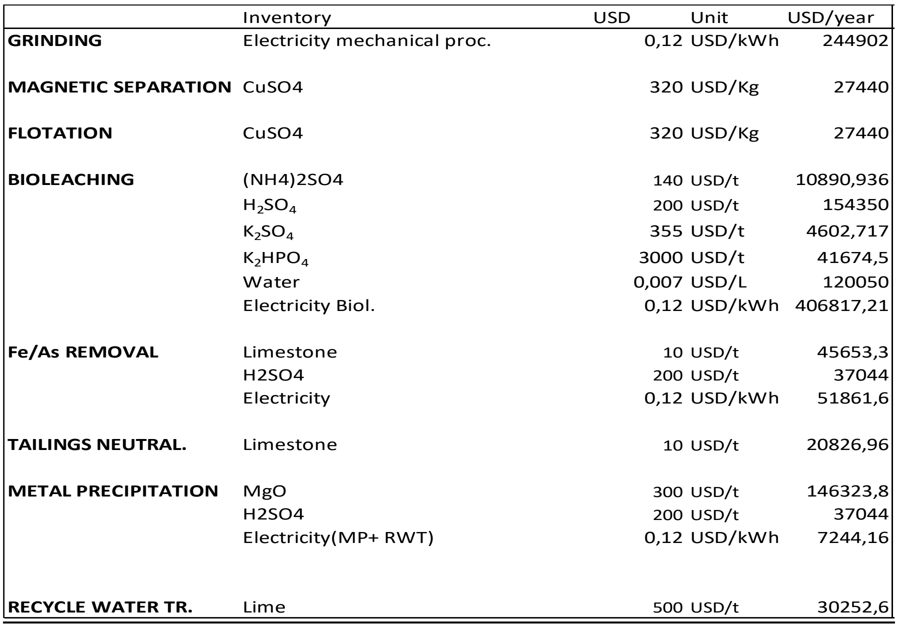
Nevertheless, some data related to the chemical products used in the bioleaching plant were not available.

In particular, the data related to the amount of gaseous CO_2 and the air flow used during the bioleaching process and the limestone and electricity used during the tailings neutralisation process were not considered during the analysis. The impacts related to the use of these substances are therefore not assessed.

Table 4.1. Life Cycle Inventory

	Inventory	Quantity/year	Unit	References & notes
F.U.: 1 year of production				
Regrinding	*Input*			
	Water	39445	t	Neale et al., 2015
	Electricity*	2040850	kWh	Personal communication with project partners
	Sulphide concentrate	12005	t	Neale et al., 2015
	Output			*electricity for the overall mechanical processes
	Sulphide concentrate	12005	t	Neale et al., 2015
Magnetic separation	*Input*			
	Sulphide concentrate	12005	t	Neale et al., 2015
	$CuSO_4$	85750	kg	Neale et al., 2015
	Output			
	Sulphide concentrate	11951,835	t	Neale et al., 2015
	3-5% Ni concentrate	53,165	t	Neale et al., 2015
Flotation	*Input*			
	water	5831	t	Neale et al., 2015
	Sulphide concentrate	11951,835	t	Neale et al., 2015
	Flotation reagent, copper sulfate	3001,25		Personal communication with project partners
	Output			
	Sulphide concentrate	6174	t	Neale et al., 2015
	flotation tailings (to dam)	5831	t	Neale et al., 2015
Bioleaching	*Input*			
	Electricity	3390143,4	kWh	Personal communication with project partners
	Sulphide concentrate	6174	t	Neale et al., 2015
	H_2SO_4	771,75	t	Neale et al., 2015
	$(NH_4)_2SO_4$	77,7924	t	Neale et al., 2015
	K_2SO_4	12,9654	t	Neale et al., 2015
	K_2HPO_4	13,8915	t	Neale et al., 2015
	Output			
	Sulphide concentrate	6174	t	Neale et al., 2015
Fe/As removal	*Input*			
	Sulphide concentrate	6174	t	Neale et al., 2015
	Limestone	4565,33	t	Personal communication with project partners
	H_2SO_4	185,22	t	Personal communication with project partners
	Electricity	432180	kWh	Personal communication with project partners
	Output			
	Gypsium	3087	t	Neale et al., 2015
	Fe/As precipitate	68,6	t	Neale et al., 2015
Tailings neutralisation	*Input*			
	Gypsium	3087	t	Neale et al., 2015
	Fe/As precipitate	68,6	t	Neale et al., 2015
	Limestone	2082,696	t	Personal communication with project partners
	Output			
	tailings (to dam)	3155,6	t	Neale et al., 2015
Metal precipitation	*Input*			
	MgO	487,746	t	Neale et al., 2015
	H_2SO_4	90,552	t	Personal communication with project partners
	Electricity	6591945.5	kWh	Personal communication with project partners
	Output			
	Metal Hydroxide Precipitate (MHP)	1001,56	t	Neale et al., 2015
Recycle water treatment	*Input*			
	Lime	60,5052	t	Personal communication with project partners
	Output			
	Clean water			return to the bioleaching tank

Table 4.2 Life Cycle Costing and Social Life Cycle Inventory



	Inventory	USD	Unit	USD/year
GRINDING	Electricity mechanical proc.	0,12	USD/kWh	244902
MAGNETIC SEPARATION	CuSO4	320	USD/Kg	27440
FLOTATION	CuSO4	320	USD/Kg	27440
BIOLEACHING	(NH4)2SO4	140	USD/t	10890,936
	H_2SO_4	200	USD/t	154350
	K_2SO_4	355	USD/t	4602,717
	K_2HPO_4	3000	USD/t	41674,5
	Water	0,007	USD/L	120050
	Electricity Biol.	0,12	USD/kWh	406817,21
Fe/As REMOVAL	Limestone	10	USD/t	45653,3
	H2SO4	200	USD/t	37044
	Electricity	0,12	USD/kWh	51861,6
TAILINGS NEUTRAL.	Limestone	10	USD/t	20826,96
METAL PRECIPITATION	MgO	300	USD/t	146323,8
	H2SO4	200	USD/t	37044
	Electricity(MP+ RWT)	0,12	USD/kWh	7244,16
RECYCLE WATER TR.	Lime	500	USD/t	30252,6

Life Cycle Impact Assessment

Once the inventory data is collected, LCIA quantifies the contribution from each elementary flow to different environmental impact category, through specific characterization models.

The characterisation can be done at midpoint level or at endpoint level. The analysis at the midpoint level assesses the contribution of the flows to environmental impact categories, while the endpoint analysis identifies the impacts damaging the Areas of Protection (AoP): ecosystem, human health, and natural resources (European Commission, 2010).

Ecoinvent 3.6 database is used to perform the study. The midpoint and endpoint analysis in this study are performed with a widely accepted environmental impact assessment method called Recipe (2016).

Life Cycle Costs Assessment

The project's total yearly financial profit is calculated. In particular, the analysis enhances the costs sustained for each process of the Mondo Minerals plant, through the calculation of the total operational expenditure (OPEX).

To perform this analysis, the costs of the single material and energy flows and the capital expenditure (CAPEX) are estimated.

Social Life Cycle Assessment

Once the data are collected, the LCIA assesses the contribution of each flow to the different social impact categories. The database used is PSILCA, and the impact assessment method used is the Social Impact Weighting Method.

Results

Life Cycle Assessment

Midpoint results

The midpoint results of the LCA regarding the analysed impact categories of the metal recover from sulphide mine tailings are presented in the following figure.

Results presented analyses the impacts caused by each material and energy flows considered in the system boundaries.

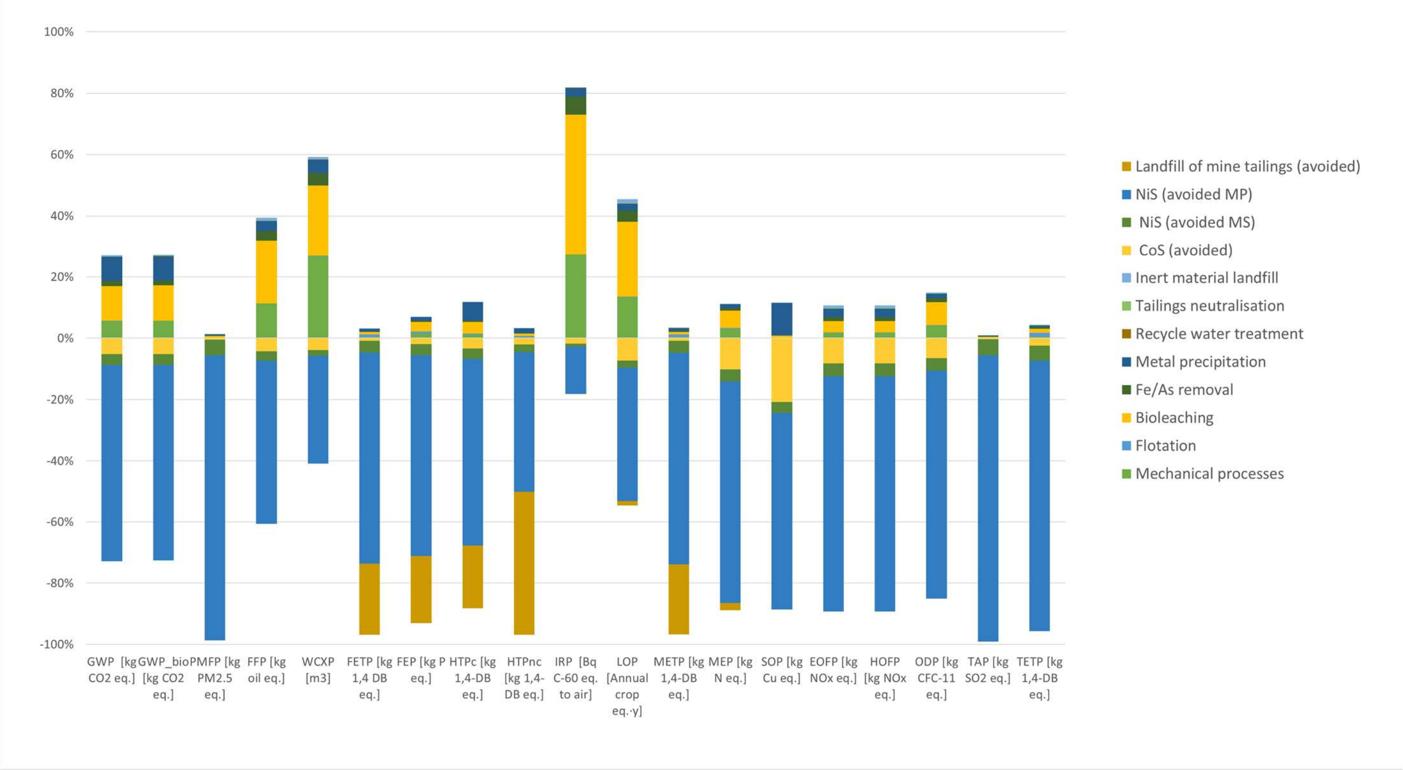


Figure 5.1 Midpoint results

For most categories, there is a greater negative impact, meaning that the avoided impact is higher than the caused impact. An example is given by the Global Warming Potential (GWP) impact category, which shows that the avoided production of nickel concentrate from new resources constitutes the 60% of the avoided impact for the GWP impact category. For the same category, the electricity consumption of the mechanical and bioleaching process contributes for almost the 20% of the caused impact.

If we look at the contribution of the single processes with a positive impact, the energy consumption gives the highest contribution in all categories, from the mechanical processes and the bioleaching process. For the freshwater consumption and ionizing radiation categories, the electricity consumption contributes respectively to almost the 90% and the 50% of the caused impact.

The use of magnesium oxide in the metal precipitation process is responsible for the caused impact in the impact category Stratosferic Ozone Depletion (SOP) and contributes for the 10% to the GWP impact categories.

If we look at the avoided production of nickel concentrate from new resources, it has the highest negative contribution in all the graphed categories. For example, it constitutes for 90% of the avoided impact for the Fine Particular Matter Formation (PMFP) impact category.

A significant negative contribution is also given by the avoided landfill of the sulphate tailings for the categories freshwater ecotoxicity, freshwater eutrophication, marine ecotoxicity, and human toxicity, where it contributes up to the 40% of the avoided impact.

A minor negative contribution to the avoided impacts is observed by the avoided production of cobalt concentrate, especially to the impact category metal depletion, where it represents the 20% of the avoided impact.

Endpoint results

The environmental LCA was also investigated at the endpoint level. The results are summarized in the following figure and represent the total environmental load as damage to resources, ecosystem, and human health.

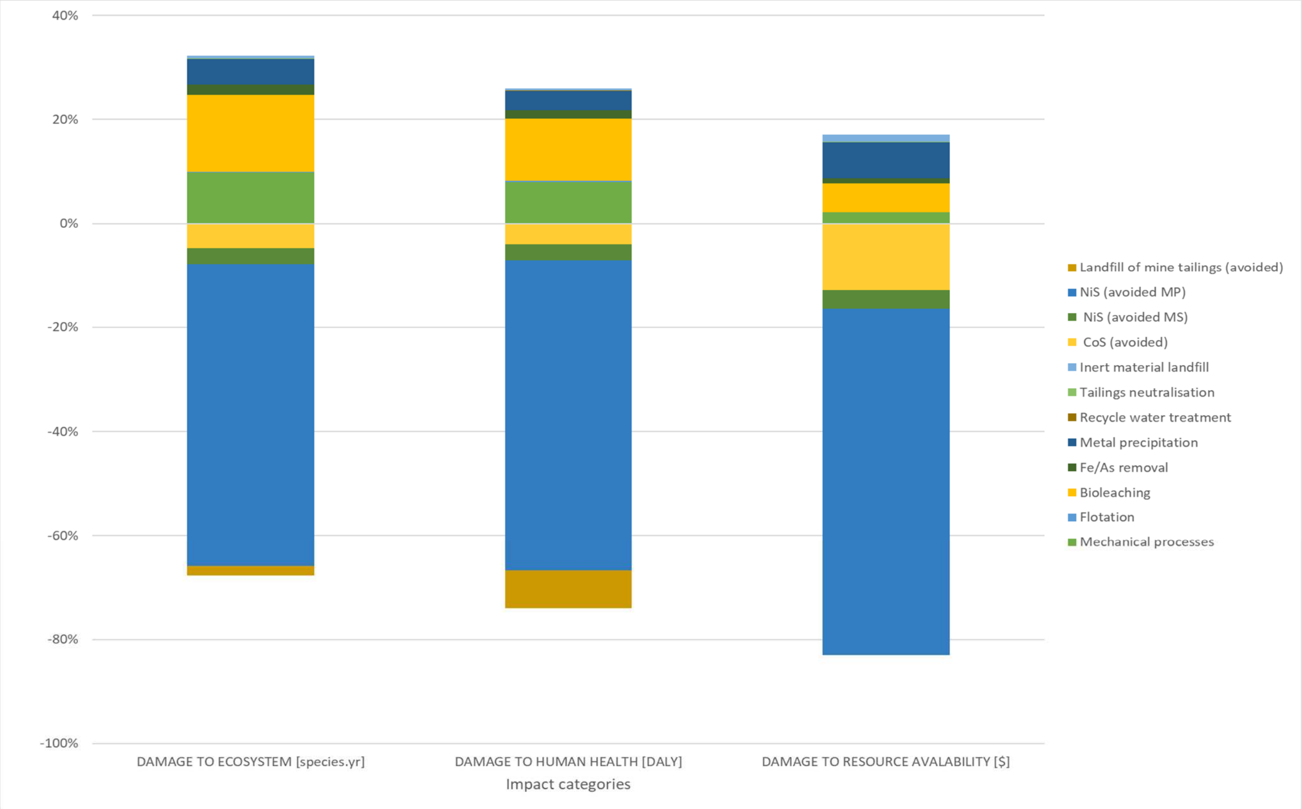


Figure 5.2 Endpoint results

For all the endpoint categories, there is a greater negative impact, meaning that the avoided impact is higher than the caused impact. The avoided production of nickel concentrate from new resources contributes the most to the avoided impact in the three categories. It contributes respectively for the 90%, 85% and 84% of the avoided impact for the endpoint categories ecosystem, human health, and resource availability.

A minor contribution to the avoided impacts is observed by the avoided production of cobalt concentrates from new resources. It contributes for the 16% of the avoided impacts on the endpoint category resource availability, for the 7% on the ecosystem category, and for the 5% on the human heath category.

The avoided landfill of mine tailings from the Vuonos and Sotkamo talc production contributes to 10% to the avoided impacts on the human health category and for 3% on the ecosystem category.

The overall electricity consumption of the project contributes for more than the 60% of the caused impacts in the endpoint categories ecosystem and human health, and for the 35% in the resource availability category.

The use of MgO (during the metal precipitation process) contributes for the 34% on the caused impacts on the impact category resource availability, while it contributes only for the 9% to the other impact categories.

Life Cycle Costing

The aim of the LCC is to assess the financial impacts of the Mondo Minerals project. In this analysis, the yearly operational costs (OPEX) for the company are calculated.

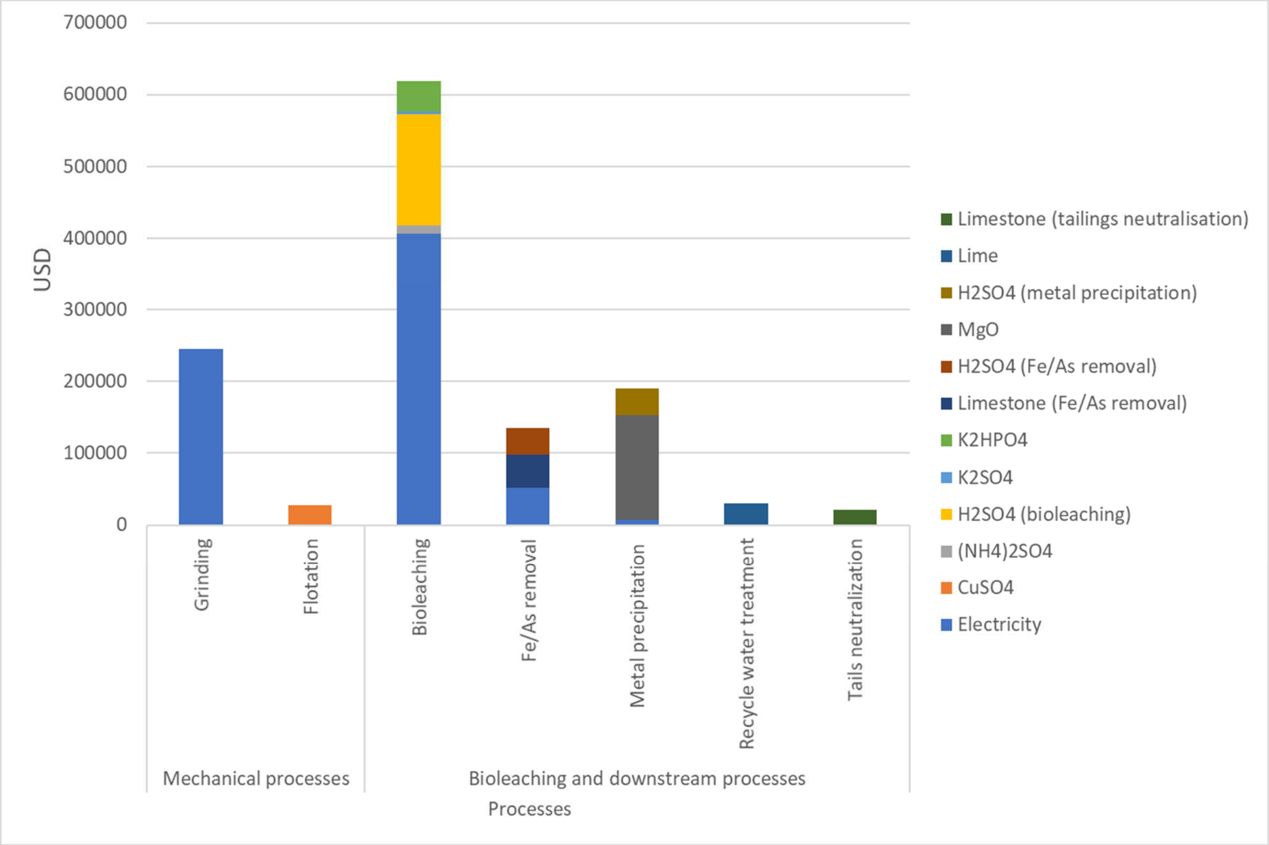


Figure 5.3 Life Cycle Costing results

The bioleaching process contributes the most to the operational costs for the company. This is mainly due to the electricity consumption, followed by the costs of chemicals.

The total yearly OPEX for the company approximately amounts to 2.5 million USD. The capital costs (CAPEX), as reported by Neale et. al (2015) amounts to approximately 15 million USD.

The profitability of the bioleaching plant is calculated through the Net Present Value (NPV). The NPV represents the present value of the cash flows at the required rate of return of your project compared to your initial investment. Basically, it is a way to calculate the return of the investment for a project. If the NPV is >0, the project is profitable.

The NPV was calculated as follow:

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_o$$

Equation 5.1 Net Present Value formula where C_t is the yearly profit(revenues-costs), r is the discount rate (10%), C_0 is the initial CAPEX and t is the time (in this case is 20 years).

The revenues are due to the nickel and cobalt concentrate sell. The price considered is 14.000 USD/tonne.

From the calculation of the NPV, the project results to be profitable:

$$\text{NPV}=\sum_{t=1}^{20} \frac{12733072}{(1+0,1)^{20}} - 15.000.000=84.912.565$$

Social Life Cycle Assessment

The SLCA in this study aims to identify the main potential social hotspot associated with the bioleaching project under study.

The stakeholder categories assessed are workers, local communities, and society. The results are presented for each stakeholder category.

The activity variable: worker hours

The results are expressed in worker hours, which is the activity variable in PSILCA, representing the social risks in the life cycle of the process under study used to describe the relevance of the impacts assessed.

Worker hours, strictly speaking, is related only to the workers stakeholder. Nevertheless, it is applied to all the stakeholder indicators, while other activity variable that suit better the other stakeholder categories indicators are currently being assessed (Maister et al., 2020).

This activity variable is referred to 1 USD of a product or sector output. The calculation is carried out with the following formulas:

$$\textbf{Worker hours} = \frac{\textbf{Unit labour costs}}{\textbf{Mean hourly labour cost (per employee)}}$$

$$\text{Unit labour costs} = \frac{\text{Compensation of employees (in USD per country}-\text{specific sector and year)}}{\text{Gross output (in USD per country}-\text{sector and year)}}$$

Equation 5.2 Calculation of the worker hours (Maister et al., 2020)

The data for the mean hourly labour costs are available from the International Labour Organization (ILO 2015a). The compensation of employee is to describe the net and gross salary with data providedby the Eora satellite accounts (Eora 2015). The gross output is equal to the average consumption plus value added of each group of producing unit (Maister et al., 2020).

Results

The results are expressed in medium worker hours for 1 tonne of nickel concentrate production in one year.

The analysis is conducted using the PSILCA database. The output results were expressed showing the impacts mostly on social indicators. To follow the Social Life Cycle Assessment guidelines and to present the results for each stakeholder category, the social indicators were aggregated in the respective social impact (sub)categories).

While in the LCA analysis it emerged the potential avoided impacts from the implementation of the project, in the social analysis is not the case.

Stakeholder category: workers

The results concerning the workers stakeholder category are presented in the following figure.

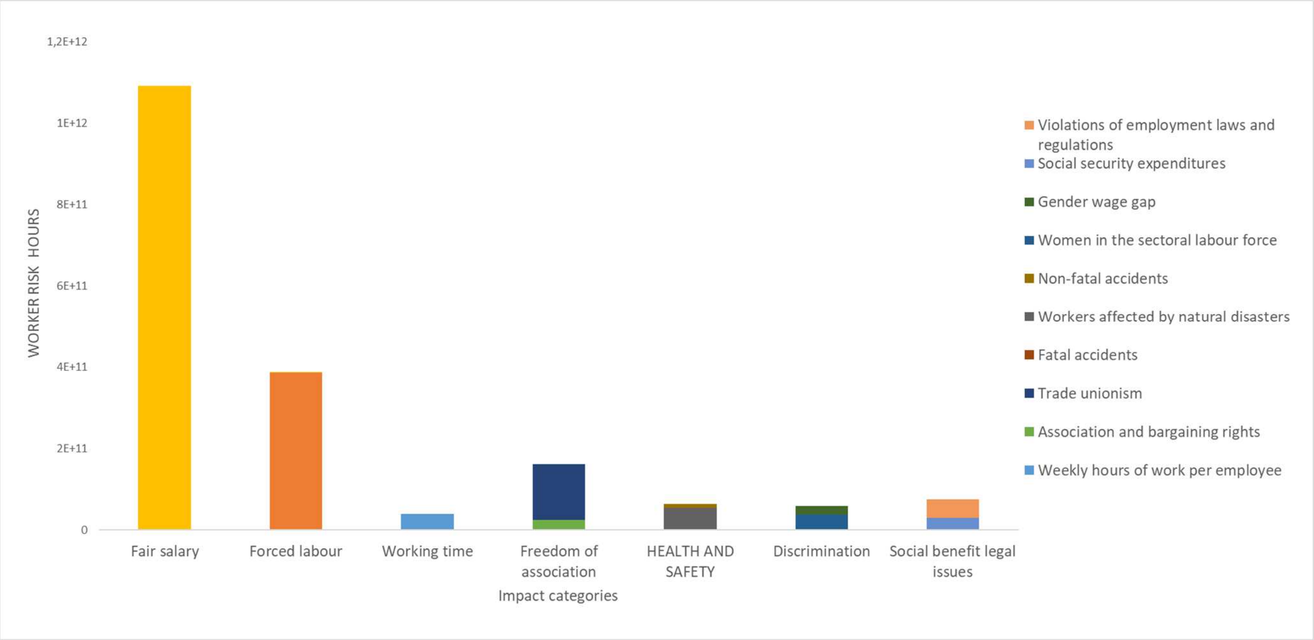


Figure 5.4 Impacts results on the workers stakeholder category

The most impacted category is fair salary, followed by forced labour and freedom of association.

The impact category fair salary refers to a salary reasonably commensurate with the value of the service rendered (Maister et al., 2020).

The reasons for such results can be further investigated.

Fair salary

Considering the impact category fair salary, the process that contributes the most is not directly linked to the project, but it occurs in the upstream chain, as shown in the following figure.

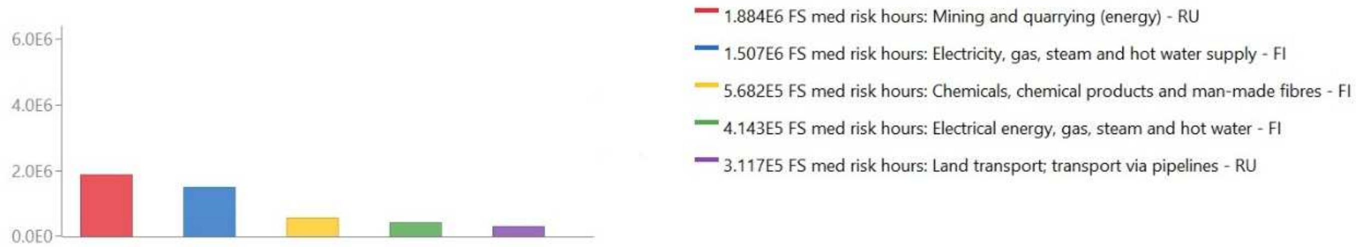


Figure 5.5 Process contribution to the impact category "Fair salary" (screenshots from openLCA 1.7)

For the impact category Fair salary, the process that contributes the most is Mining and quarrying (energy)-RU.

For a S-LCA, it can be important to localise the impacts, as shown in the following figure.

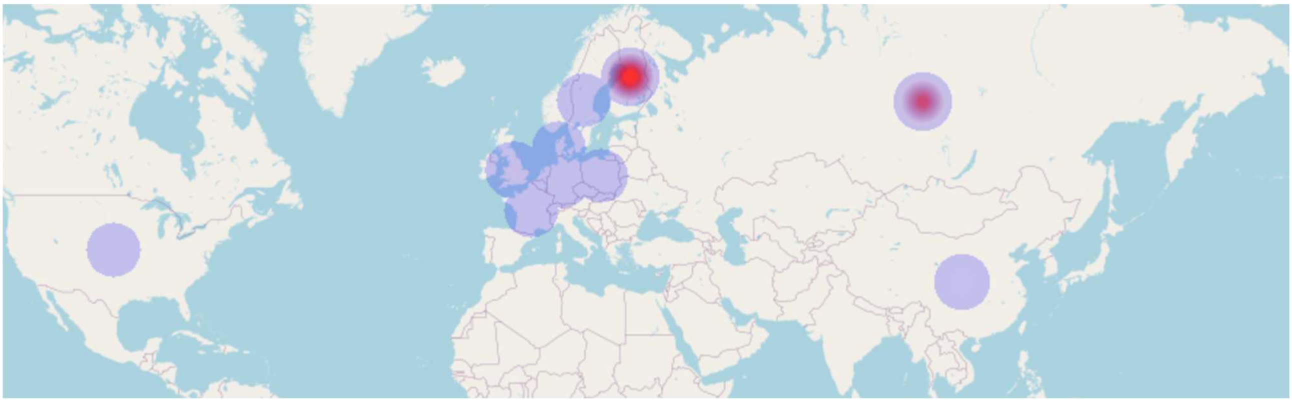


Figure 5.6 Geographic localisation of the "Fair salary" impact category" (screenshots from openLCA 1.7)

The impacts result to be situated mostly in Finland and Russia, while some impacts are located in a few European countries.

Forced labour

A similar situation occurs with the forced labour category, where "Mining and quarrying (energy)-RU" is the most contributing process along the supply chain, as shown in the following figure:

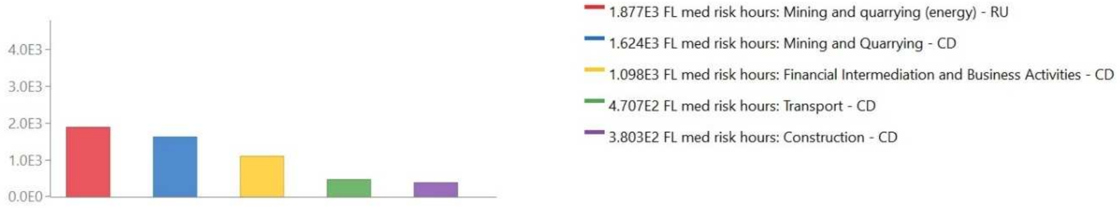


Figure 5.7 Process contribution to the impact category "Forced labour" (screenshots from openLCA 1.7)

While the mentioned process is the most contributing one, the impact are located especially in South Africa, as shown in the following, followed by Russia.

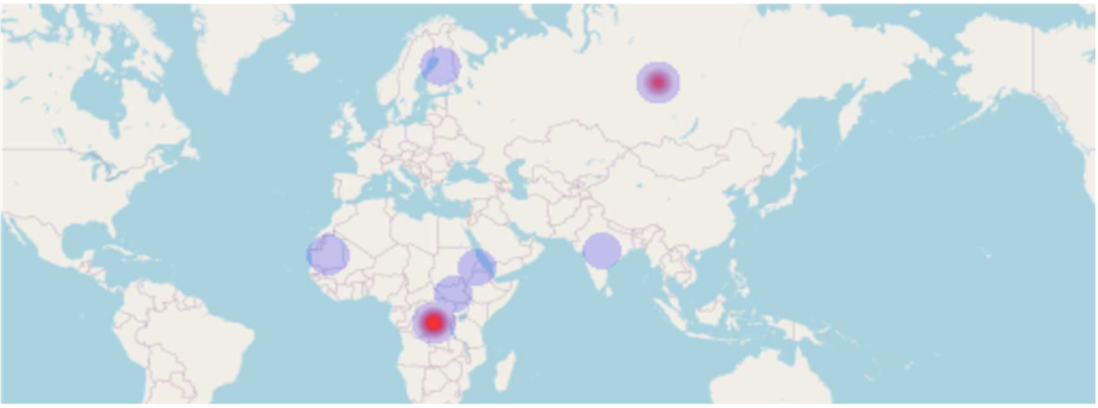


Figure 5.8 Geographic localisation of the "Forced labour" impact category (screenshots from openLCA 1.7

Stakeholder category: local community

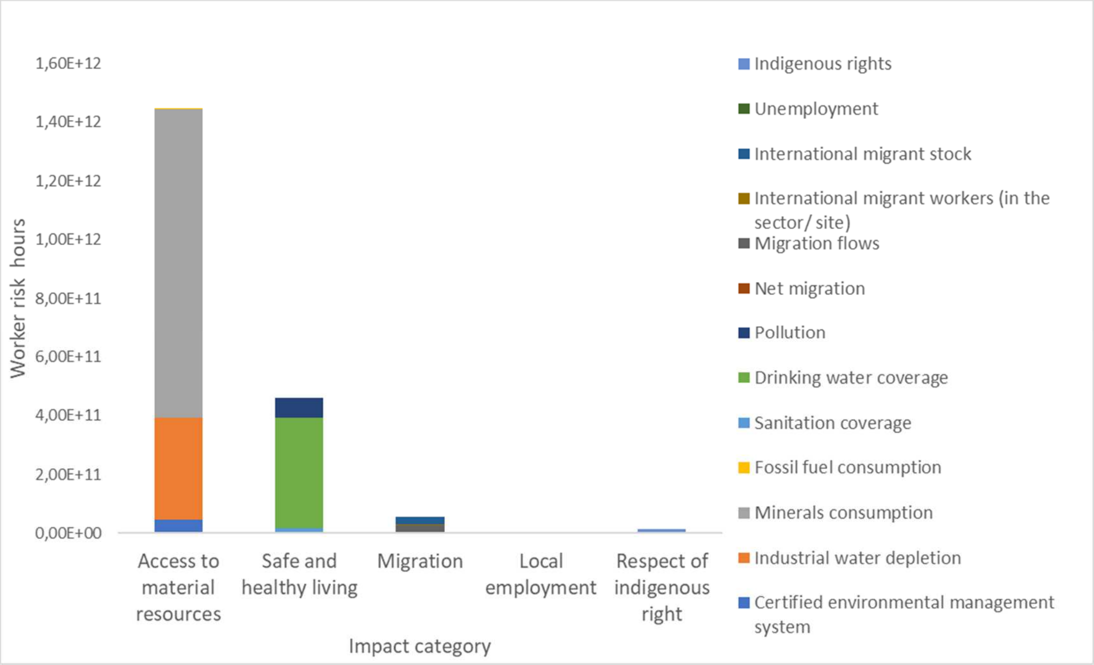


Figure 5.9 Impacts results on the local community stakeholder category

For local community category, the most impacted categories are access to material resources, due mainly to the minerals consumption indicator, and the safe and healthy living, due to the impacts on Drinking water coverage indicator.

Further investigation can be done, identifying the most contributing process along the upstream chain.

Access to material resources
As an example, the contributions to the Access to material resources impact category are analysed.

- *Minerals consumption*

The following graph shows the contribution of the processes in the upstream chain to the minerals consumption indicator. The most contributing process is the “Mining and quarrying (energy)-RU”, followed by “Electricity, gas, steam and hot water supply-FI”

Figure 5.10 Process contribution to the social indicator "Minerals consumption" (screenshots from openLCA 1.7)

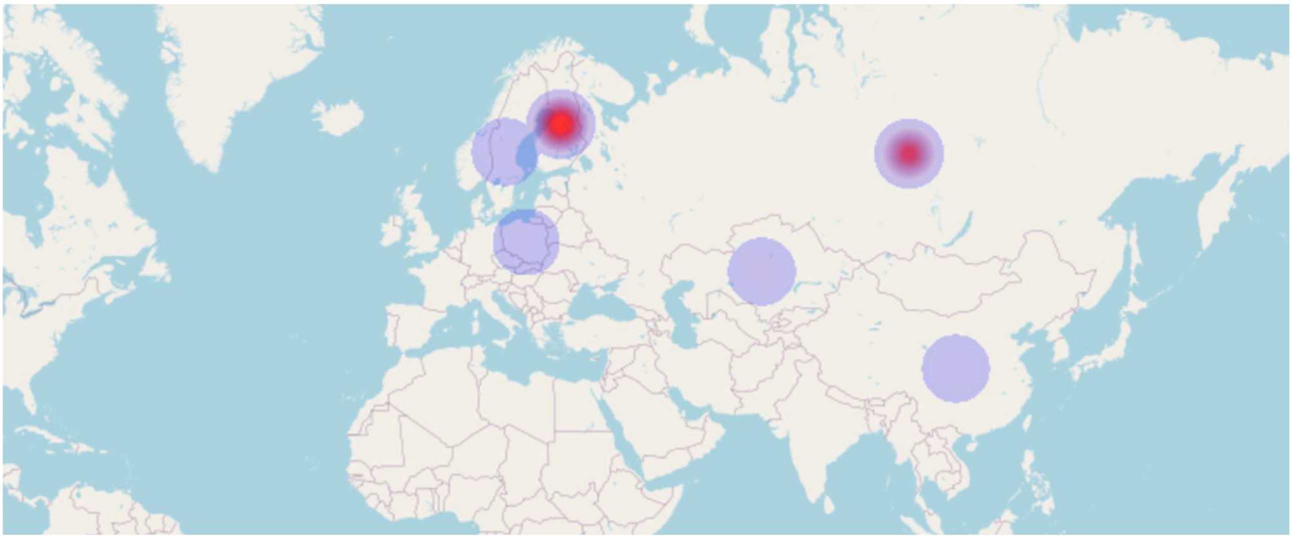


Figure 5.11 Geographic localisation of the "Minerals consumption" social indicator (screenshots from openLCA 1.7)

As shown in the figure, most of the impacts for the minerals consumption are in Finland and Russia.

- *Industrial water depletion*

The most contribution processes regarding the industrial water depletion indicator are highlighted in the following graph:

Figure 13. Process contribution to the social indicator "Industrial water depletion" (screenshots from openLCA 1.7)

The most contributing process is the Electricity, gas, steam, and hot water supply-FI. Most of the impacts, as also shown in the following figure, are located in Finland, followed by Germany and few other European countries.

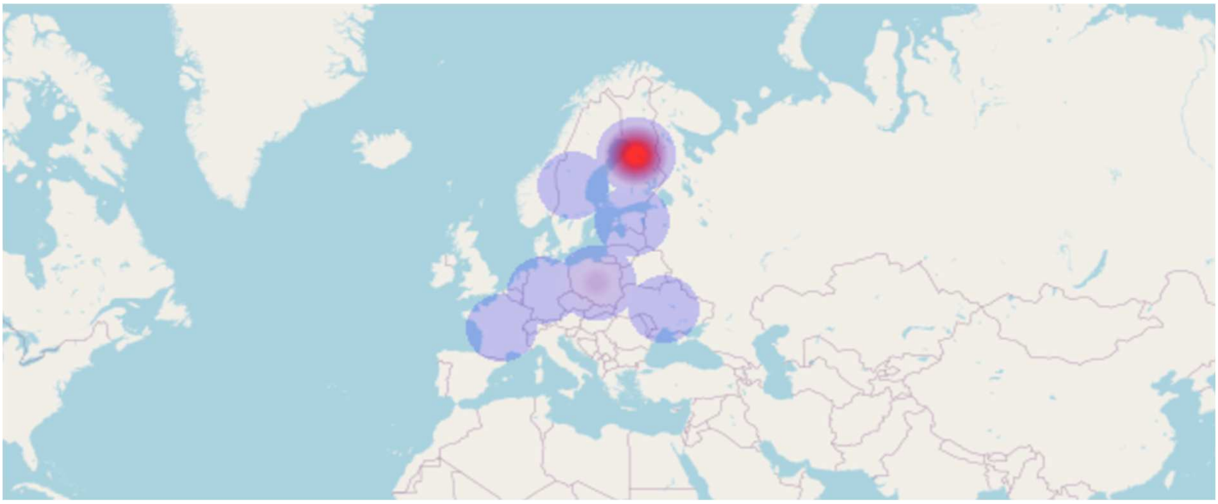


Figure 5.12 Geographic localisation of the " Industrial water depletion " social indicator (screenshots from openLCA 1.7)

- *Certified environmental management system*

The contributions of the single processes to the total amount of risk hours in minimum.

Figure 5.13 Process contribution to the social indicator "Certified environmental management system" (screenshots from openLCA 1.7)

The first five processes contributes for less than 20% of the total, therefore it is necessary to look at the map of the impacts to have a clearer idea of the impacts locations.

In this case, the impacts are mainly located in Finland and few European countries like UK, Poland and Ukraine, and USA.

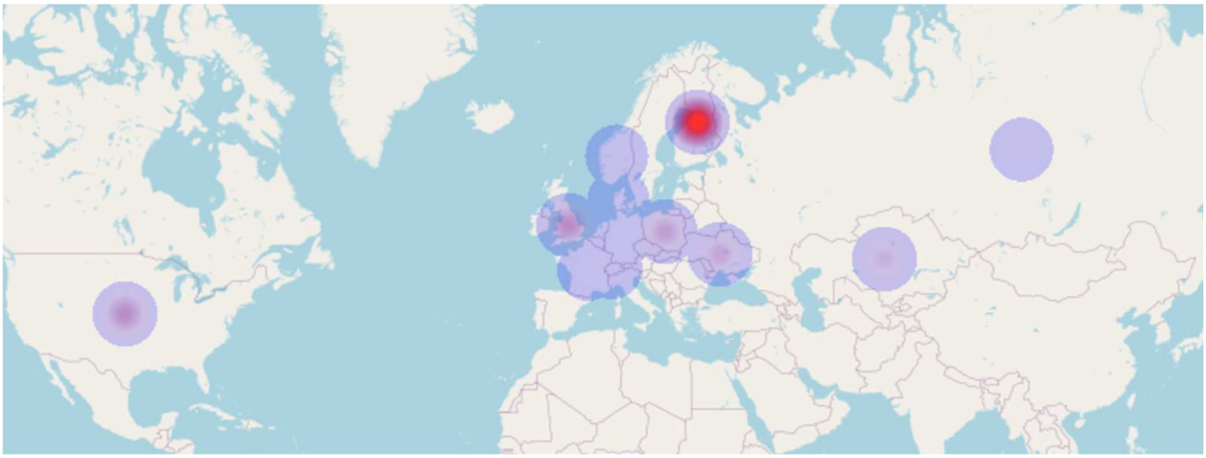


Figure 5.14 Geographic localisation of the " Certified environmental management system " social indicator (screenshots from openLCA 1.7)

Summarizing the results for the access to material resources impact category, it seems that the major contributions are given by the upstream chain processes mining and quarrying (energy)-RU and Electricity, gas, steam, and hot water supply-FI. Most of the impacts are in Finland and Russia.

Stakeholder category: society

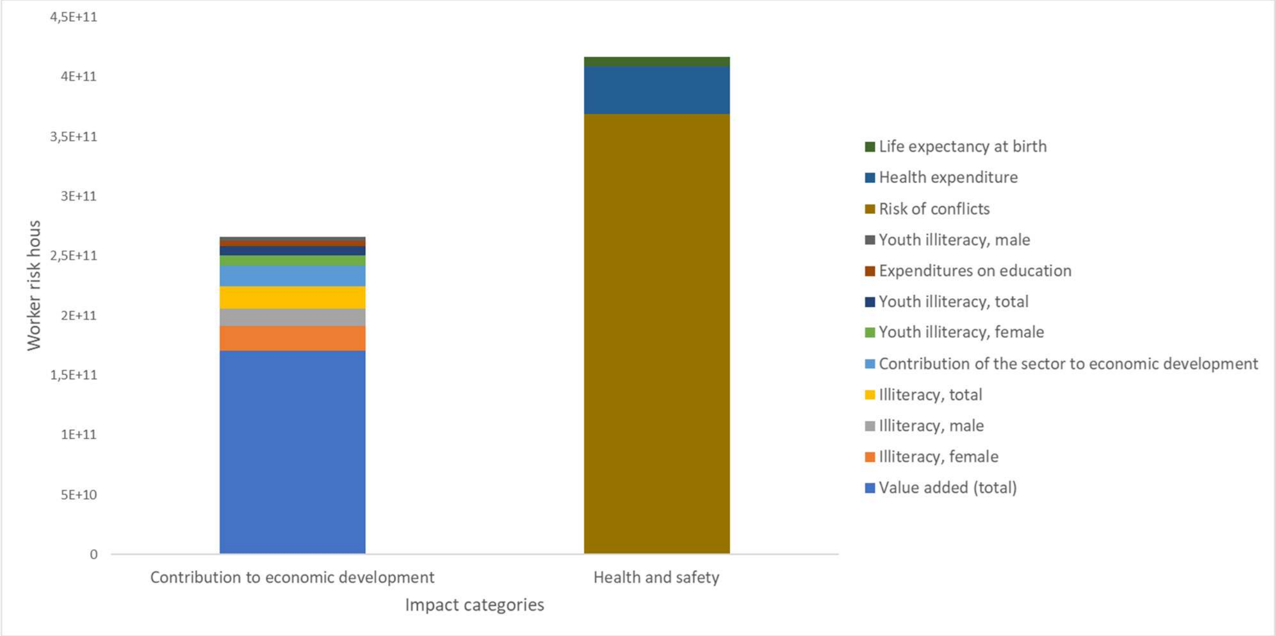


Figure 5.15 Impacts results on the society stakeholder category

For the society stakeholder category, there are only two impact categories. The most impacted one is the health and safety, mainly due to the contribution of the risk of conflicts social indicator.

Health and safety

- *Risk of conflicts*

The most contributing indicator for the health and safety category is the risk of conflicts.

As shown in the following graph, Mining and quarrying (energy)-RU is the most contributing process.

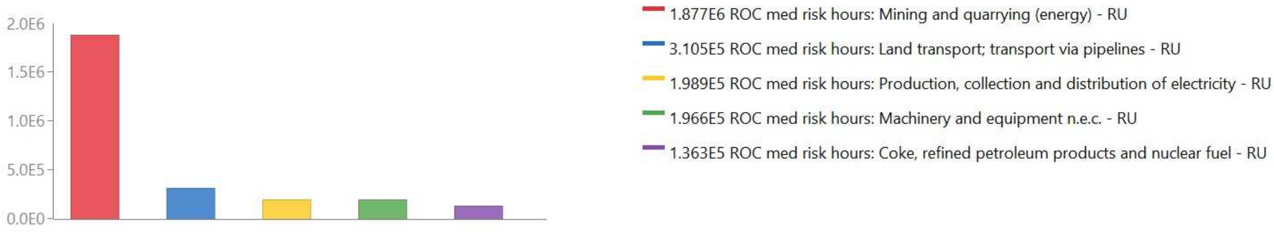


Figure 5.16 Process contribution to the social indicator "Risk of conflicts" (screenshots from openLCA 1.7)

In fact, most of the impacts are located in Russia, while only a little contribution is given by the impacts located in Congo and Ukraine.

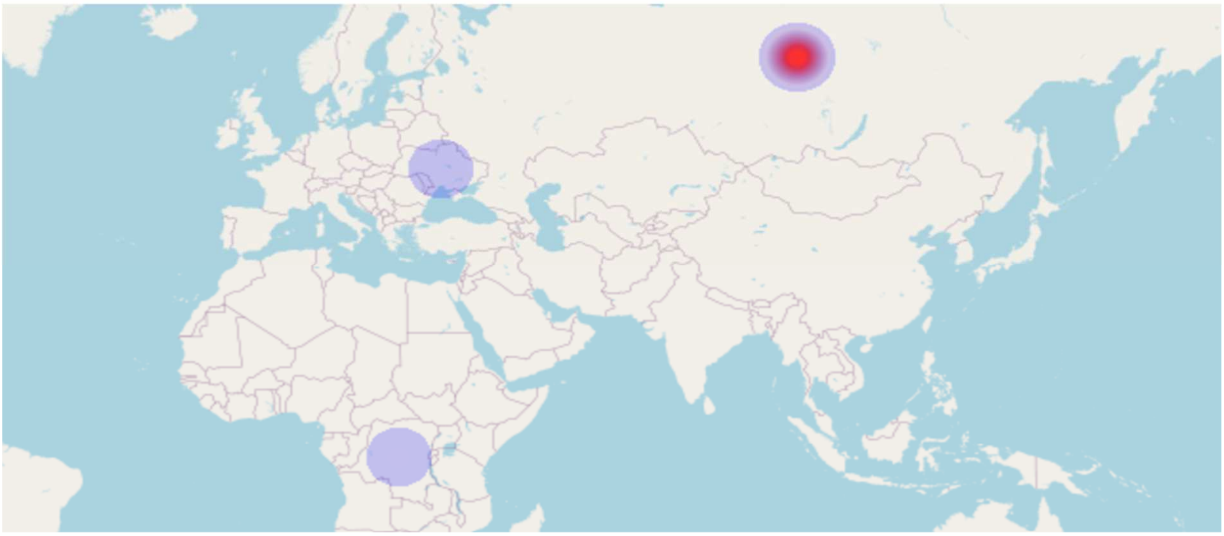


Figure 5.17 Geographic localisation of the "Risk of conflicts" social indicator (screenshots from openLCA 1.7)

- *Health expenditure*

It is one of the key indicators to assess the health systems of countries, essential to combat disease and improve the health of populations (Maister et al., 2020).

The most contributing process is Mining and quarrying (energy)-RU, followed by mining and quarrying-CD.

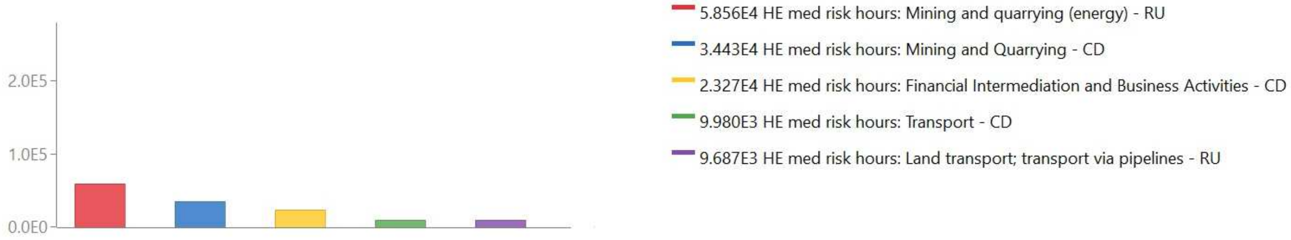


Figure 14. Process contribution to the social indicator "Heath expenditure" (screenshots from openLCA 1.7)

In fact, most of the impacts are located in Russia and Congo, followed by India, China and Finland.

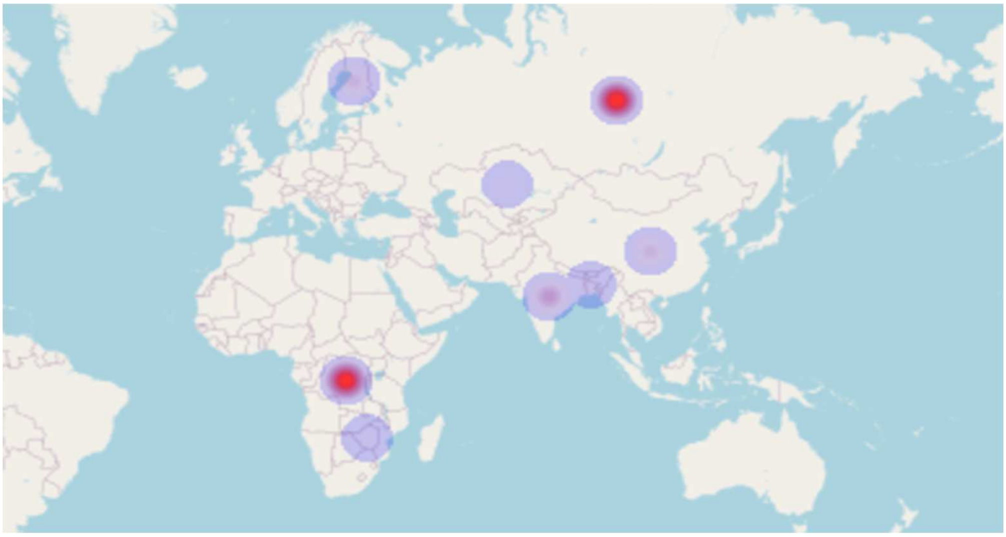


Figure 15. Geographic localisation of the "Health expenditure" social indicator (screenshots from openLCA 1.7

Conclusions

Mine tailings represent one of the main sources of contamination of waters and soils during mining activities, if not safely stored. However, they can also represent an opportunity, since these residues contain great amounts of valuable metals that can be extracted. These extractions from mine tailings can help to reduce the environmental impacts of mining activities and avoid the huge remediation costs, which often relies on local communities. The usual extraction methods are not convenient on mine tailings, due to their low minerals' grade. Therefore, new techniques for the recycling of mine tailings are needed to extract valuable metals. As first of its kind, this study aims at assessing the sustainability of mine tailings using the Mondo Minerals bioleaching plant project as a case study. The aim of this case study is to recover nickel and cobalt from Vuonos and Sotkamo mine tailings. The methods used are based on the Life Cycle Approach.

The LCA analysis shows that the bioleaching process contributes the most to the environmental impacts derived from the implementation of the plant. Nevertheless, the main feature of the project is its contribution in avoiding production of nickel and cobalt concentrates from new resources, hence reducing other several environmental impacts.

Results from the LCC analysis show that the company's main costs are linked to the bioleaching process, caused by electricity consumption and the chemicals used.

For the S-LCA analysis three main stakeholder categories were selected to assess the impacts: workers, local community, and society. From the results it emerged that a fair salary (or the absence of it) impacts the workers the most. Instead, the local community stakeholder category impacts are related to the access to material resources, while the health and safety category is the most impacted category for the society stakeholder. Most of the impacts are related to processes in the upstream chain.

These economic and environmental analyses demonstrate that the recovery of tailings represents an actual opportunity to reduce the environmental impacts of metals extraction, and it is also an opportunity to increase the profitability of mine tailings for the mine company. Moreover, it helps reducing the amounts of metals extracted from new resources, therefore limiting the use of new resources for their production.

This study also demonstrates that the extraction of metals from mine residues through new technologies, like bioleaching, at least in this specific case, are economically profitable.

Mine tailings recycling, despite its potential, is an opportunity that only few mining companies are considering. Reasons behind this choice are due to the high investment's costs, the low concentration of metals in mining residues, and the presence of dangerous metals, such as arsenic, that makes the extraction more difficult and more expensive. To incentivize the industries toward the recycling of mine tailings, governmental strategies can be taken, such as the increase of mine residues disposal tax, that would make the costs of landfilling higher that the costs for the recovery of metals.

The methodologies

LCA, S-LCA and LCC are based on the life cycle approach, thus all of them follow the same steps to assess respectively the environmental, social, and economic sustainability of a project. Despite that, while the LCA is a widely used and standardized approach, S-LCA is still under development and needs to be further defined and structured.

Regarding in particular the S-LCA performed for this thesis, some considerations can be done.

The analysis was conducted using PSILCA, a database specifically developed to assess the social impacts of products and services. The development of PSILCA is quite recent, and still needs to be further implemented. Indeed, if compared to other databases for environmental analysis, such as Ecoinvent, it is quite poor in available processes.

Considering that the S-LCA is a site-specific analysis, the possibility to select a specific region within the process selected (in addition to the country) can be useful to have more site-specific results.

Furthermore, the results obtained with PSILCA are not immediately easy to understand and to present. If the aim is to follow the S-LCA guidelines, the impacts must be assessed on the different stakeholder categories, through the analysis of the social impact subcategories (described by the social indicators). However, in PSILCA, the results are assessed mostly on the social indicators. Thus, to present the results on the stakeholder categories, the social indicators must be aggregated, making the analysis more difficult and time consuming.

Another aspect to consider is that PSILCA builds the results based on energy and mass flows (the same as LCA), while S-LCA is a site-specific assessment: it is not strictly related to mass and energy flows but to the different stakeholders involved in the project (workers, local communities, society). Thus, they are not directly related to the input and output flows, therefore the social analysis based on those can be misleading.

Besides these limits, PSILCA is a promising database, which can be useful for a preliminary social hotspots analysis, from which further on-site investigations can be done to identify the main causes of the social impacts.

As previously said, while the LCA methodology is widely used and well defined, the S-LCA is still under development. The application of the guidelines helps to identify the methodology's strengths and weakness points, allowing to make further improvement.

Conducting the different analyses in parallel is useful to assess all the impacts related to the project and to identify the common hotspots and the trade-offs between the three different pillars of sustainability: environment, economy, and society. This can be helpful for the implementation of the Mondo Minerals' project: the company can decide if and where are the main hotspots and where it should focus to improve the plant performances.

For instance, in this case the results show that the bioleaching process, among all the others, is the most impactful one, at least from the environmental and economic point of view. Thus, the decision makers can focus on this process to make the bioleaching plant more sustainable both economically and environmentally. Another example is increasing the energy efficiency of the processes or changing the source of energy (considering other options, such as renewable energy) may be helpful to improve the performances of the bioleaching plant.

Another aspect to consider is that often the environmental, economic, and social impacts are related to each other. The environmental damages occurring in the area surrounding a mine site leads to a great economic impact and the remediation costs can be huge, impacting other activities, such as fishing and agriculture, caused by contamination. Consequently, the latter can lead to direct harm on workers and local communities. Conducting these three analyses in parallel does not highlight these chained, and interconnected, relationships. Hence, it is crucial to develop a common framework assessing the sustainability of a product, service, or project from all the sides when presenting these same results to decision-makers.

Different frameworks are currently under development, but they still are not well defined and need further implementations. The combination and integration of the three different analyses will be the next step towards a complete sustainability assessment. As previously said, the trade-offs between economic, environmental, and social performances of a project cannot be fully taken into account when the methods are used separately. One of the major concerns for the combination of the methodologies is the fact that the results provided by LCA, LCC and S-LCA are based on different units. For example, while the LCC is based on monetary flows, in LCA they are based on physical quantities. Thus, it is difficult to combine the results in a unified form, which can facilitate understanding the results provided.

In conclusion, pursuing the aim of this thesis, the sustainability analysis presented underlines the potential benefits derived from the recovery of mine tailings that can be a valuable solution to reduce the impacts linked to mine tailings on the environment. Furthermore, the latter demonstrates the economically feasibility of the metal recovery, the processes that can be further implemented, and the social hotspots of the project. Additionally, it provides a possible way to present clearly the Social LCA results and follow the S-LCA guidelines.

The work carried out in this thesis highlights the potential areas of improvement of the sustainability assessment methodologies, focusing on the Social Life Cycle Assessment, which improvement is necessary to develop a standardized method.

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