Feasibility of re-processing mine tailings to obtain critical raw materials using real options analysis

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Abstract

The re-processing of mine tailings to obtain critical raw materials (CRMs) could reduce the mining of new deposits as well as ensure the profitable use of the waste materials. Though, it requires large scale industrial installations and the development of specialized technologies to obtain CRMs. New investment in mining activities is an operation, engaging for considerable financial resources involved. The scale of such an endeavor makes a new mining activity a high-risk operation due to several uncertainties present. Therefore, there is an acute need to use new tools to assess the risk associated with the planning and development of new mining activities.

This study introduces a framework to evaluate the economic risk related to the re-processing of mine tailings to obtain CRMs. The framework, based on real options analysis (ROA), and sensitivity and uncertainty analysis, was applied to analyze the profitability of using mine tailings as a source of CRMs in the Chilean mining industry. The novelty of this approach consists in enabling the investment decision making including the uncertainties related to a novel investment mining project.

Results show that tailing storage facilities in Chile have some stocks of CRMs, like scandium, whose extraction could be profitable. For the data used, the results of uncertainty and sensitivity analyses show that capital expenditure has a more significant influence than the other variables. Therefore, for the case of mine tailings re-processing, it is essential to develop processes and technologies that enable lower capital expenses.

Keywords: Critical Raw Materials; Real Options; Circular Economy; Mine Tailings Valorization; Mine Tailings Management; Net Present Value

1. Introduction

Mine tailings are waste obtained after the processing of some minerals to acquire one or more elements of interest. They are composed of a mixture of heavy metals, water, sand, and fine-grained solid material, and generally are deposited in ponds without further treatment (Babel et al., 2016; Santibañez et al., 2012; L. Wang et al., 2017). The annual amount of mine tailings generated by the mining industry exceeds 10 billion tons (Adiansyah et al., 2015) and is expected to be growing because of the increasing production forecast by 2035 the volume of tailings will double (CESCO, 2019). Due to higher demand for mineral products and lower grades of ore as a result of which more materials will have to be processed in more energy-intensive processes (Wang et al., 2014). Particularly, Chile has already 10,565 million tons of mine tailings and an approved capacity of 23,935 million tons, from which 99% belongs to mines of copper-gold-silver-molybdenum resources (SERNAGEOMIN, 2020).

Mine tailings deposits may contain many valuable elements as has been shown in several studies (Alcalde et al., 2018; Andersson et al., 2018; Figueiredo et al., 2018; Khalil et al., 2019; Khorasanipour and Jafari, 2017; Macías-Macías et al., 2019; Markovaara-Koivisto et al., 2018; Medas et al., 2013; Wen et al., 2019). In the particular case of Chilean copper mine tailings, 0.82% are metals, non-metals, and metalloids, 0.01% rare earth elements, and the rest major rock-forming elements (SERNAGEOMIN, 2017). Nowadays, mine tailings are increasingly often seen as a potential source of raw materials, and secondary sources are attracting more and more attention due to the benefits of a circular economy approach (Jeswiet, 2017; Kinnunen and Kaksonen, 2019).

Currently, extracting raw materials and metals from ore bodies of declining ore grade means potentially bigger mine size generating more waste, overburden to the environment, higher consumption of energy, water, and auxiliary materials which overall produce severe environmental consequences and larger political risks (de Koning et al., 2018; Mudd, 2010; Northey et al., 2016; Žibret et al., 2020). Furthermore, by 2050 the overall demand for metals will rise by a factor of 3-4 (de Koning et al., 2018). When a mine has exhausted its resources whose extraction is economically viable, an alternative is to close it and then reopen when the market and technology conditions enable a profitable re-processing of tailings (Northey et al., 2016). The long-term supply of metals highly depends on actual and expected prices, cumulative availability curve, and new mining technologies (de Koning et al., 2018; Gordon et al., 2007; Tilton and Lagos, 2007; Yaksic and Tilton, 2009). Additionally, the development of new high-tech technologies might lead to disruptive demand change (Tukker, 2014); meanwhile, it may take ten years or more to open new mines and adjust production (de Koning et al., 2018)

There is a group of materials that is drawing considerable attention, recently. They are called critical raw materials (CRMs) and are fundamental to the manufacturing of a broad range of equipment essential in digital technologies, low-carbon systems, and sustainable mobility (David and Koch, 2019; Mathieux et al., 2017; X. Wang et al., 2017). According to the European Commission, critical raw materials possess two common characteristics: they have high economic importance to the European Union and their supply is associated with high risk (European Commission, 2017). Supply risk results from the concentration of primary supply in the countries, considered as risky due to their governance performance and trade aspects (European Commission, 2017). The recent list made by the European Commission contains 30 raw materials or groups of raw materials that are identified as critical (European Commission, 2020).

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Mine tailings contain several CRMs, even if their content is low, the volumes of mine tailings are big enough to consider re-processing (Binnemans et al., 2015; Careddu et al., 2018). Several studies analyze the geochemical content of mine tailings to demonstrate that they contain CRMs and point out that tailings could be re-processed in the future (Ceniceros-Gómez et al., 2018; Dino et al., 2018; Markovaara-Koivisto et al., 2018; Moran-Palacios et al., 2019; Tunsu et al., 2019).

This study aims to propose a framework to assess the feasibility of re-processing mine tailings to obtain CRMs considering the uncertainties involved. The presented methodology is illustrated by the set of unique data applicable to Chilean mine tailings. The proposed approach consists of applying the Discounted Cash Flow (DCF) method alongside Real Options Analysis (ROA) as well as uncertainty and sensitivity analysis. It could be applied to other mine tailings deposits for which geochemical data are available. For example, the contents of CRMs in mine tailings have been already measured in some deposits in Finland, Sweden, Portugal, Indonesia, and Mexico (Ceniceros-Gómez et al., 2018; Hällström et al., 2018; Markovaara-Koivisto et al., 2018; Peelman et al., 2018; Szamałek et al., 2013; Tunsu et al., 2019).

The research questions that this study seeks to answer are:

- Is it economically feasible to invest in a project developed around the idea of re-processing mine tailings to obtain critical raw materials?
- How can real options analysis improve the decision to invest in a project using mine tailings as a source of critical raw materials?
- How can the net present value variables influence real options performance?

Sustainable development components involved in mine tailings management strategy should include energy, water, technology, environmental impact, cost (Adiansyah et al., 2015), and policy. The valorization of mine tailings appears a critical component to achieving a circular economy model in the mining industry, which needs to improve its processes to minimize the environmental impacts of mining waste (Lèbre et al., 2017; Tayebi-Khorami et al., 2019). The valorization of tailings is still in the early stages, but it is expected to improve in the future (Kinnunen and Kaksonen, 2019). Economic tools are crucial to analyze the use of secondary sources (Alwaeli, 2011a). The proposed approach consists of applying the Discounted Cash Flow (DCF) method alongside Real Options Analysis (ROA) as well as uncertainty and sensitivity analysis.

The novel contribution of this article consists of considering ROA and sensitivity and uncertainty analysis to give flexibility to the economic assessment of mine tailings re-processing, acknowledging the uncertainties involved. Net present value (NPV, which is a metric to assess the feasibility of a project, is calculated using the DCF method as a starting point, and next using ROA, different outcomes for an investment project are estimated (Arnold, 2014; Brandão et al., 2005; Kodukula and Papudesu, 2006; Trigeorgis, 1996). The viability of mining investments depends on variables that have high uncertainty as to the market prices of metals. In the case of re-processing mine tailings, technology developments and business model development are still needed. To study the influence of several variables on NPV outcome, Monte Carlo simulation is used to perform sensitivity and uncertainty analysis.

2. Methodology

The profitability analysis of mine tailings processing requires the identification of geochemical characteristics of the tailings deposit, also named tailings storage facility (TSF). Mineral characteristics and concentration of elements that are present in the TSF along with the mass of tailings accumulated in the deposit allow estimating the quantity of each CRM (Araya et al., 2020; Markovaara-Koivisto et al., 2018; Moran-Palacios et al., 2019).

In the economic analysis, the in-situ value is estimated by multiplying the total mass of a specific CRM by its price. Total mass is calculated based on the average concentration and mass in a TSF (Araya et al., 2020; Markovaara-Koivisto et al., 2018). DCF method is used to estimate the NPV of a project for extracting one or more CRMs from one of the TSF analyzed. Criteria used to choose which CRM could be extracted include concentration, total mass, and price. In some cases, finding such data, as well as get access to data for estimating the capital expenses (CAPEX) and the operating expenses (OPEX) for each CRM is rather difficult.

Subsequently, an overview of technologies suitable for re-processing mine waste stored in a TSF to extract the CRMs is needed. If these technologies are still not applicable on an industrial scale, then, technologies used to process primary ores to obtain such CRM are considered, the same goes for economic inputs such as CAPEX, OPEX, and production. When dealing with mine waste, some consideration needs to be given to aspects, such as a lower grade of elements contained in it (Araya et al., 2020; Binnemans et al., 2015; Falagán et al., 2017). Mine tailings are already in the form of a paste or slurry, so there are no mining costs, which usually represent 43% of operating costs in a mine (Curry et al., 2014).

ROA is applied using the NPV obtained with the DCF method using the method of risk-neutral probabilities presented in. The binomial tree analysis is used to apply ROA. A binomial tree is built by using the method of risk-neutral probabilities presented by Kodukula and Papudesu (2006); this methodology involves adjusting the risk of the cash flows across the lattice with risk-neutral probabilities and discounting them at a risk-free rate (Kodukula and Papudesu, 2006). Sensitivity and uncertainty analyses are used to assess the effect of uncertainties on net present value. Monte Carlo simulation is used to perform uncertainty analysis and the Sobol’ indices are calculated to perform global sensitivity analysis.

2.1. Project valuation tools

Investments in the mining sector are capital intensive and mostly irrevocable with a limited economic life span. Their economic viability depends on the uncertain world market price and on how project risks emerge (Guj and Chandra, 2019). The project value is determined by the commodity market and flexibility inherent in the metal mining system to respond to uncertainties (Savolainen et al., 2017). The available future metal prices can be used as certain in the project valuation process, where their maturity is maximum between two to five years (Savolainen, 2016).

Traditional valuation tools, such as the DCF method, are static methods that do not consider the uncertainty of the variables used to estimate the profitability of an investment (Arnold, 2014; Brandão et al., 2005; Kodukula and Papudesu, 2006; Trigeorgis, 1996). The project valuation techniques that ignore the real option nature of the project are widely used in the mining industry, e.g., net present value, internal rate of return, and static DCF (Savolainen, 2016). DCF method treats future cash flows as deterministic values. Methods to include uncertainty in the result of NPV are: increasing the discount rate, applying sensitivity analysis, comparing pessimistic and optimistic cash flows, or to use scenario planning to estimate expected cash flows (Gaspars-Wieloch, 2019).

There are many approaches to analyze cost-intensive investments under the conditions of uncertainty (Cristóbal et al., 2013). One of the methods gaining popularity is real options as it is being applied in different fields (Insley, 2002; Nelson et al., 2013; Regan et al., 2015; Schatzki, 2003; Slade, 2001). Real options are a right, not an obligation, to undertake business initiatives connected with tangible assets (Kodukula and Papudesu, 2006; Wang and Neufville, 2005). Real options acknowledge managerial flexibility and readiness to adjust investment projects due to future uncertainty and the changing environment, involving possible managerial options that can reshape a project and adapt it to changing conditions to maintain or enhance its profitability (Trigeorgis, 1993). Real options for a project exploit the flexibility of sequential investment with flexible strategies and the capability to delay decisions in an engineering system to react to an uncertain outcome; where the changes depend on exogenous and endogenous uncertainties, so it is hard to make credible value estimates (Guj and Chandra, 2019). Common attributes of real options valuation design include identification of sources of uncertainty, available real options recognition, modeling of uncertain variables, and real option valuation (Kozlova, 2017). Methods used to evaluate real options are decision trees, Monte Carlo simulations, and the Black-Scholes model (Arnold, 2014; Collan, 2011; Kodukula and Papudesu, 2006).

ROA is used in metal mining to assess mining investments due to the growing market uncertainty and project complexity of new investments. The real options valuation method aims to protect and increase the economic return from a project (Savolainen, 2016) and is applied predominantly in investment project valuation (Kozlova, 2017).

2.2. Discounted Cash Flow (DCF) method

DCF method is based on the calculation of NPV of a project over its entire life cycle accounting for the investment and the free cash flows throughout its whole life (Kodukula and Papudesu, 2006).

$$Project\ NPV = PV\ of\ free\ cash\ flows\ in\ production\ phase - PV\ of\ investments\ costs \quad (1)$$

According to the DCF method, if the project *NPV* is greater than zero, it means that the project revenues are greater than the costs of the project, so it is financially attractive (Arnold, 2014; Kodukula and Papudesu, 2006).

Present value *(PV)* is the estimation of costs and net revenues of the development production phase. These are the free cash flows over the entire life cycle of the project (Kodukula and Papudesu, 2006).

$$PV = \frac{FV}{(1+r)^n} \qquad (2)$$

Where *FV* is the future value, *r* is the discount rate per time period, and *n* is the number of the time period.

To estimate the NPV of a project, CAPEX and OPEX of a project with similar characteristics in terms of ore grade and production capacity are used. CAPEX may include treatment equipment, water intake structure, site preparation, concentrate discharge system, auxiliary equipment, piping, and valves (Bhojwani et al., 2019). OPEX includes labor, energy cost, chemicals, maintenance, spare parts, as well as indirect cost (Bhojwani et al., 2019).

The following equation was employed to estimate NPV and PV of a project based on the use of mine tailings:

$$cash\ flow = \left(price \cdot production - OPEX \cdot production - \frac{CAPEX}{n}\right) \cdot (1 - taxes) + \frac{CAPEX}{n} \quad (3)$$

$$Annuity = 1 - \frac{1}{\frac{(1+R)^n}{R}} \qquad (4)$$

$$PV = cash\ flow \cdot annuity \qquad (5)$$

$$NPV = PV - CAPEX \qquad (6)$$

Where n is the time of the project development, and r is the discount rate or interest rate. The equations formulated replace calculating cash flows for every year of the project and then adding them up to calculate the PV.

2.3. Sensitivity and Uncertainty Analysis

A project is based on many inputs that are uncertain, such as production costs, price of materials and equipment, and sales volume. The analysis and modeling of uncertainty enhance the ability to make appropriate decisions. The need to analyze uncertainties comes from the awareness that data abundance does not necessarily provide certitude, and sometimes can lead to errors in the decision-making process (Attoh-Okine and Ayyub, 2005). Due to uncertainty, there is no project without risk, and the uncertainty could be caused by different factors, e.g. lack of information or data (Munier, 2014).

Sensitivity analysis examines the response or reaction of an output variable, such as the NPV to the variations of input variables, such as price or sales volume, etc. (Munier, 2014). Sensitivity analysis methods explore and quantify the impact of possible errors in the input data on predicted model outputs (Loucks and van Beek, 2005). Sensitivity analysis is used in a broad spectrum of disciplines to study how various sources of uncertainty in a model contribute to the model's overall uncertainty. On the other hand, uncertainty analysis assesses the impact of ambiguous values of parameters on the final results (Cacuci, 2003). Sensitivity analysis may be performed together with uncertainty analysis to ensure the quality of the model and the transparency of the decision-making process (Borgonovo, 2017).

Monte Carlo simulation methods are tools widely used to perform sensitivity and uncertainty analysis (Attoh-Okine and Ayyub, 2005). Monte Carlo simulation can be used for risk analysis by modeling the probability of the different outcomes of a process; it can be used as a valuation tool for projects (Arnold, 2014; Collan, 2011; Kodukula and Papudesu, 2006). Monte Carlo simulation randomly generates values of the uncertain variables within a certain range to simulate the potential outcomes (Kodukula and Papudesu, 2006; Mun, 2002). Sensitivity and uncertainty analysis can be used as a complementary tool to the DCF method and ROA to study the effect of the inputs on NPV (De Reyck et al., 2008; Gaspars-Wieloch, 2019; Kodukula and Papudesu, 2006; Pivorienė, 2017).

2.4. Real Options Analysis (ROA)

A ROA or real options valuation (ROV) is performed alongside the DCF method; ROA is applied using PV of free cash flows and NPV of a project calculated with DCF method as a basis to estimate different outcomes (Kodukula and Papudesu, 2006). Traditional options used in ROA are the option to defer or the option to wait to invest in a project, expand a project, and an option to choose between projects (Kodukula and Papudesu, 2006).

In this study, a binomial tree is used, which is a decision tree. The binomial model can be solved using risk-neutral probabilities or market-replicating portfolios, both have the same theoretical framework leading to the same solutions but with different mathematical approaches (Kodukula and Papudesu, 2006). The inputs required to build a binomial tree and calculate the option value are the risk-free rate *(r)*, the value of the underlying asset (S_0) which is the PV of the expected free cash flows based on the DFC method, the cost of exercising the option *(X)* which is the investment required, the life of the option *(T)*, the volatility factor *(σ)* which is a measure of the variability of the underlying asset during its lifetime, and the time frame chosen for the calculations *(δt)* (Kodukula and Papudesu, 2006). In Figure 1, a generic binomial tree of 2 steps is shown.

The up *(u)* and down *(d)* factors are functions of the volatility of the underlying asset, and they are described as follows:

$$u = \exp(\sigma\sqrt{\delta t}) \qquad (7)$$

$$d = \frac{1}{u} \qquad (8)$$

The risk-neutral probability is a mathematical intermediate that allows for discounting the cash flows using a risk-free interest rate. The risk-neutral probability *(p)* is defined as follows:

$$p = \frac{\exp(r\delta t) - d}{u - d} \qquad (9)$$

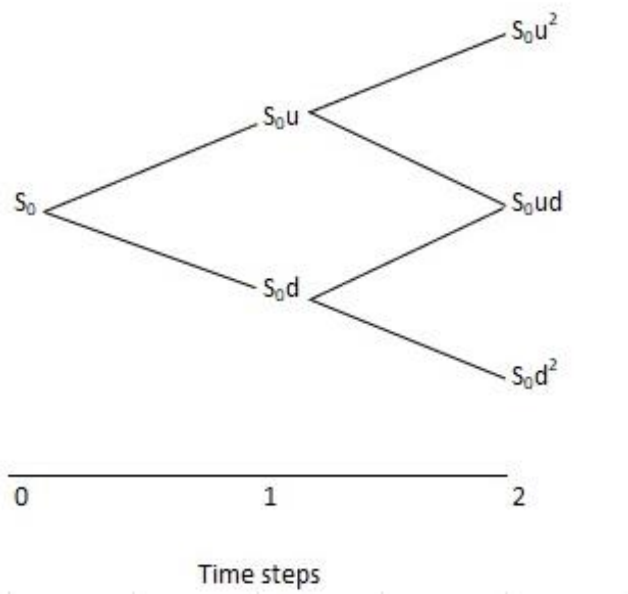

Figure 1: Generic recombining binomial tree (source: adapted from Kodukula and Papudesu, 2006).

The option to wait also called the option to defer should be included in every project. A company may prefer to wait before it invests in a project with either negative or marginal NPV when it is highly uncertain that the project will achieve a high NPV in the future (Kodukula and Papudesu, 2006). An example is a delay in mining a deposit until the market conditions are favorable.

3. Case study

Chile has a large mining industry (Cisternas and Gálvez, 2014; Jane, 2003); mining represents 9.8% of the gross domestic product, and copper mining is responsible for 8.9% (COCHILCO, 2019). Chile has a rich territory endowed with porphyric deposits in terms of copper and molybdenum (Oyarzún and Oyarzún, 2011). In 2018, Chile produced 5,872 million fine copper tons equivalent to 28.3% of global production, which made it the No. 1 world producer of copper (SERNAGEOMIN, 2019a). The country is also the second world producer of molybdenum, a copper by-product, with 60,248 tons representing 20.4% of the world's production.

The production of copper in Chile is concentrated mainly in the northern and central parts of the country, where 40% of the worldwide reserves of copper are found (SERNAGEOMIN, 2019a). Copper can be found in sulfide ores and oxides. Sulfide ores are the primary source of copper. Copper is obtained from sulfide ores by flotation to concentrate copper; mine tailings are the waste of flotation.

In Chile, there are 740 tailing storage facilities. Most of them come from copper mining, and all are registered in a national cadaster kept by The National Service of Geology and Mining - SERNAGEOMIN, out of which geochemical characteristics of 634 tailing deposits are available online, 56 chemical elements have been analyzed, including 25 CRMs. The content of silicon dioxide is also analyzed because silicon metal is a CRM that can be obtained from silicon dioxide (SERNAGEOMIN, 2019b).

The Antofagasta Region is located in the Atacama Desert in northern Chile, and it holds the largest tailings deposits in the country, including the biggest one with a capacity of 4,500 million tons (SERNAGEOMIN, 2020). This study is focused on active tailing deposits, i.e., those currently used until they reach the legally allowed capacity. These tailing deposits are Laguna Seca, Talabre, Esperanza, Sierra Gorda, and Mantos Blancos; the location of these mine tailings deposits is shown in Figure 2. The capacity of the active mine tailings analyzed in this study is presented in Table 1. In the supplementary material, the detailed geochemical characterization of the analyzed deposits is included.

Table 1: Allowed capacity in active tailings storage facilities in Antofagasta Region, source:(SERNAGEOMIN, 2020).

Tailing storage facility (TSF)	10^6 t (until 23.04.2019)	10^6 t (allowed capacity)
Laguna Seca	1,302.24	4,500
Talabre	1,792.72	2,103.95
Sierra Gorda	142.80	1,350
Esperanza	240.50	750
Mantos Blancos	130.71	138.2

Figure 2: Active TSF located in the Antofagasta Region, source: (SERNAGEOMIN, 2020).

4. Results

Despite low concentrations of CRMs found in mine tailings, these appear as possible sources of CRMs due to their availability in larger volumes and the ease with which they can be treated on-site using the geochemical analysis provided by SERNAGEOMIN, which shows the average concentration of 56 chemical elements present in tailing facilities (SERNAGEOMIN, 2019b). The total mass of each CRM contained in the TSF was calculated using its average concentration and the mass of the tailing facility. The in-situ values were calculated using current prices, in some cases when it was not possible to find the price of the CRM as metal, the price of the oxide was used, so these are estimates based on the available data provided by the United States Geological Survey in their report about commodities released in 2019 (U.S. Geological Survey, 2019), the prices that were not available in this report were taken from websites providing metal prices (Metal Prices, 2019; Statista, 2019). The average concentration, total mass, and price of each CRM of Esperanza TSF appear in Table 2 as an example. The same calculations for the other four TSF analyzed can be found in Supplementary Material. In Table 2, it is also presented the price of the mischmetal, which is an alloy of rare earth elements, usually 50% cerium and 25% lanthanum with smaller amounts of neodymium and praseodymium (Sciencedirect, 2020).

Table 2: Concentration, mass, and in-situ values of critical raw materials in the Esperanza tailing storage facility.

Critical raw materials	**Average concentration (mg/kg)**	**Mass (t)**	**Price (USD$/t)**	**CRM in-situ value (10^6 USD$)**
Vanadium	160	120,000	30,865	3,704
Cobalt	11	8,250	72,753	600
Niobium	21	15,750	21,000	331
Barium	185	138,750	180	25
Hafnium	3.88	2,910	775,000	2,255
Silicon	224,632	168,474,330	3,042	512,563
Yttrium †	49	36,750	36,000	1,323

Scandium †	26	19,500	5,420,000	105,690
Lanthanum †	15.96	11,970	2,000	24
Cerium †	32.32	24,240	4,830	117
Praseodymium †	4.31	3,233	92,400	299
Neodymium †	17.46	13,095	51,000	668
Samarium †	3.65	2,738	14,850	41
Europium †	1.06	795	56,000	45
Gadolinium †	3.43	2,573	22,330	57
Terbium †	0.49	368	647,500	238
Dysprosium †	2.87	2,153	280,700	604
Holmium †	0.55	413	38,000	16
Erbium †	1.71	1,283	140,000	180
Thulium †	0.26	195	not available	0
Ytterbium †	1.6	1,200	not available	0
Lutetium †	0.23	173	1,258,000	217
Mischmetal †	85.9	63,630	20,300	1,292

†: rare earth elements

The profitability of using mine tailings as a source of CRMs is analyzed using a ROA to produce a CRM using the examined TSF. The ROA is illustrated using the option to wait if the investment is not an attractive option according to the results of the DFC method. Reasons to wait to invest include situations when capital cost and/or operating costs are too high, and the prices of CRMs are not high enough to obtain a positive NPV for the project.

The example used to illustrate this analysis is the production of scandium metal. Scandium was chosen as a CRM to be extracted from mine tailings out of Table 2 due to its elevated price and the quantity present in the TSF, as well as the availability of data about CAPEX and OPEX for a similar project of scandium production. Scandium is not reported to be recovered from mine tailings; it is produced mainly from primary resources and the principal source for scandium is metal imports from China (U.S. Geological Survey, 2019), from REE, and iron ore processing in Bayan Obo, China (European Commission, 2017). Hydrometallurgy processes have been suggested to recover scandium from secondary sources.

4.1. Discounted Cash Flow method and Net Present Value

The data for the production of scandium from primary resources were used to estimate PV and NPV (Investorintel, 2014). The following considerations were made to adapt the data from the original report to the case of mine tailings: the concentration of scandium in the tailing deposits is ten times lower than in the primary resource, hence it was considered that CAPEX and OPEX would be ten times higher. However mining and comminution costs are not considered since there is no need to incur these costs when dealing with mine tailings, in the case of the OPEX, 43% is discounted from the original values since that percentage corresponds to mining and comminution processes (Curry et al., 2014). To have a realistic and profitable process, lower production volume was considered. Moreover, an 80% process efficiency was assumed. The input parameters are listed in Table 3, and they correspond to the adapted parameters from the project that was used as a reference.

Table 3: Input parameters for the Discounted Cash Flow method

Input parameters	Value	Unit
Capital expenses	333	million USD
Operating expenses	5,700	USD/t
Price of scandium metal	5.42	million USD/ t
Ore grade	26	ppm

Production	8	Ton/year
Discount rate/ interest rate	0.1	
Period	5 &10	years
Taxes rate	0.35	

The DCF method using a risk-adjusted discount rate for five years showed that the PV for the project is 195 million USD, an NPV -138 million, for an investment of 333 million USD. If the DCF method is screened for a longer period, e.g., ten years, it shows a higher value of PV and NPV, 244 million USD, and -89 million USD, respectively. It is essential to point out that traditional mining projects, planned for 15 or 20 years, are used for calculating NPV because they are long-term investment projects, but in the case of a project based on mine tailings and CRMs it is more reasonable to use a shorter period.

4.2. Uncertainty and sensitivity analysis of NPV

To study the effect of uncertainties of input variables and their distribution on NPV results and their sensitivity. Sensitivity and uncertainty analyses were performed using Monte Carlo simulation in RStudio. NPV was modeled using equations (6) to (9), which is a function of the inputs used to calculate the NPV; in this analysis, taxes, and depreciation were included. The inputs ranged between a minimum and maximum value, considering a range $\pm$20%, the following values for each output were considered: price 4.4– 6.6 million USD/ton, CAPEX 268 – 402million USD/ton, OPEX 4400 – 6600 USD/ton, discount rate 0.08 – 0.12, production 6.4 – 9.6 ton, and the number of years of the project was constant since NPV is highly sensitive to changes in the period of investment. The analysis was made for an investment of five and ten years. Fifty thousand simulations were run.

Summary of results shows, for an investment of 5 years, a minimum value of -229.03 and maximum value of -32.5 for NPV and a mean and median that are almost equal, - 137.33 and -137.47, respectively.

To perform global sensitivity analysis, the function of R-studio Soboljansen implements the Monte Carlo estimation of Sobol´ indices with independent inputs. Figure 3 shows the main and total effects of the inputs. It can be seen that the main effect and the total effect of each variable are very close which indicates that there are no significant interactions between them. A boxplot was used to confirm the results obtained by the estimation of the Sobol indices. It allows to visualize the minimum, lower quartile, median, upper quartile, and a maximum of a data set (Spitzer et al., 2014). The boxplots as a visualization method enable to represent the characteristics that might not be visible otherwise, and they are a straightforward and informative method of data interpretation (Sun and Genton, 2011). The boxplot is presented in the supplementary material. It can be seen, using the boxplot and the Sobol indices, that CAPEX in this investment has the most significant impact on NPV.

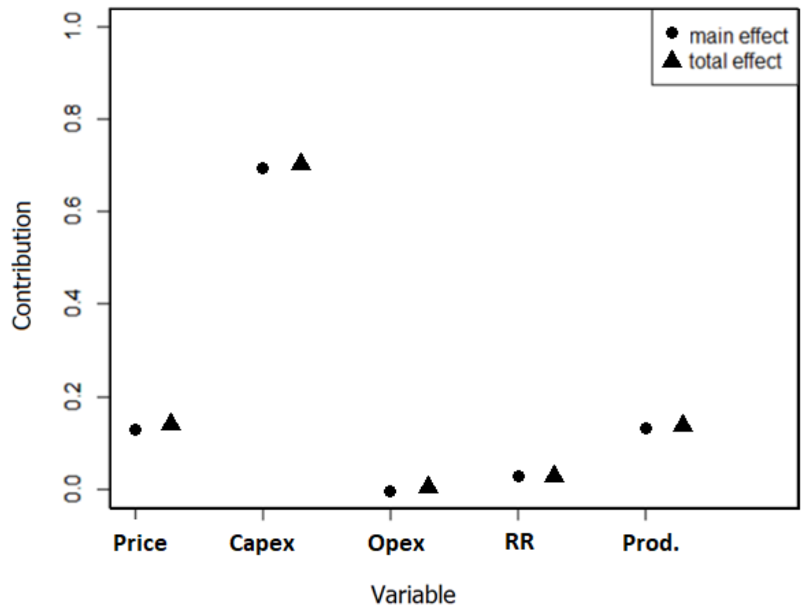

Figure 3: Sobol´-Jansen indexes for 5-years investment scandium project.

4.3. ROA using the binomial tree method

ROA is performed using a binomial decision tree methodology presented by Kodukula and Papudesu (2006), for an investment of five years and an investment of ten years. The input parameters and option parameters are shown in Table 4.

Table 4: Input and option parameters for ROA.

Input parameters		Unit
S_0 (5 years)	195	million USD
S_0 (10 years)	244	million USD
T (time to expiration)	5/10	years
X	333	million USD
σ (volatility)	30	%
r (risk-free rate)	5	%

Δt (time step)	1
<u>Option parameters</u>	
u (up factor)	1.35
d (down factor)	0.74
P (risk-neutral probability)	0.51

For the two cases, five years and ten years, option parameters are the same. Next, the development of a decision tree for an investment of five years is explained; the procedure is the same for both cases. With the option parameters, the binomial tree is built by calculating asset values and options values over the life cycle of the option; asset values are obtained after multiplying S_0 to u and d raised to the power indicated in each node. Those are the numbers on top of every node of the binomial tree. For example, in node S_0u^5, the expected asset value is 874 million USD.

Option values are the bottom numbers in the tree. The option to wait expires at the end of the binomial tree, so a decision cannot be made after the time that the decision tree takes. Option values at year five are calculated as the expected asset value of each node minus the cost of exercising the option, which corresponds to the investment. So, for example, in node S_0u^5, the expected asset value is 874 million USD, the investment is 333 million USD, then the net asset value is 541 million USD. The decision in node S_0u^5 would be to invest.

If the option value is negative, then the option value is equal to zero, because a real option is a choice, not an obligation. The option to invest is exercised at nodes where the option value is not zero.

Option values are the numbers below each node, and they are calculated with backward induction. Figure 4 shows the binomial tree for five years, and the binomial tree for ten years' investment is included in the supplementary material. Each node represents value maximization to invest in that point or to wait until the next period; at every node, there is an option to either invest in the project or the option to wait until the next period, until the option expires, the net asset value, in this case, represents the NPV. Since the option is evaluated at five-year intervals, in node S_0u^5, see Figure 5 the decision is to invest in this point, and the option value is 541 million USD, but in year five, there are also nodes where the option value is zero. In node $S_0u^3d^2$, the expected asset value is 263 million, for an investment of 333 million, the net asset value is -70 million. Hence, the option value at this point is zero, so the decision in this node would be not to invest.

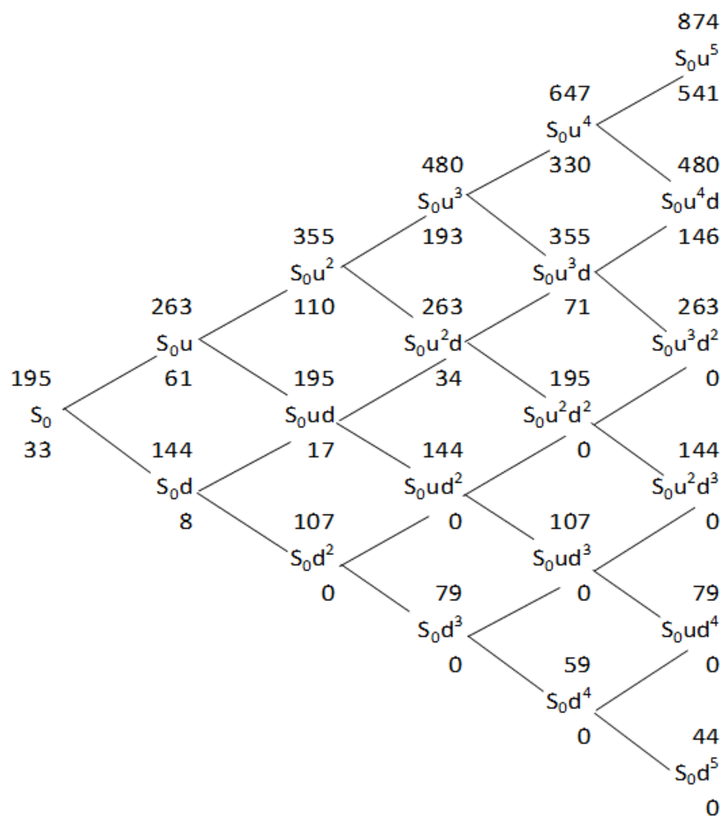

Figure 4: Binomial tree for the option to wait for five years to invest in the scandium project.

Next on the intermediate nodes, the expected asset value for keeping the option open is the discounted weighted average of potential future option values using the risk-neutral probability that value, e.g., at node S_0u^4 is:

$$p(S_0u^5) + (1-p)(S_0u^4d) \cdot exp(-r\delta t) \qquad (10)$$

In this node, if the option is exercised the payoff would be 647 million, resulting in a net asset value of 314 million, by investing 333 million, since the net asset value obtained by keeping the option open is higher, 330 million, then the option to invest is not exercised. In some intermediate nodes, the expected asset value is lower than the investment, which results in a net loss, then the decision at that node is to wait, which means that the option value is $0. The option valuation binomial tree is completed until year 0.

In each node, the upper numbers represent the expected future values of the underlying asset during the option life cycle as it evolves according to its cone of uncertainty, see Figure 5. For example, in year 2, the project is estimated to produce a total payoff between 107 and 355 million USD, at the end of year five, the payoff is between 44 and 874 million. The bottom numbers represent option values on the maximization of investing in that point or applying the option to wait until the next period. The option expires in the fifth year because it is framed in such a way that it considers competitive forces and uncertainty in the market.

Based strictly on DCF results, the payoff of the project will be 195 million USD, resulting in a negative NPV of -38 million USD, this negative outcome means that an investment is not attractive. If the decision is based exclusively on the NPV result, then the decision would be not to invest. Real options analysis provides an additional value of 33 million USD, considering a net present value of -138 million USD, the added value with real options analysis is 171 million USD. The same analysis was made for a 10-year investment as shown in the supplementary materialif the same investment is screened to 10 years, NPV based on the DCF method is -89 million, ROA analysis gives an added value of 105 million.

5. Discussion

Waste valorization is a crucial component that the mining industry must do to shift from a linear economy to a circular economy (Khaldoun et al., 2016; Kinnunen and Kaksonen, 2019). There are different approaches to mine tailings valorization, e.g., the simplest and traditional one is to recover water or to decrease water usage in the tailing stage. Other strategies consist of recovering metals from mine tailings or using mine tailings as a construction material (Ahmari and Zhang, 2012; Lam et al., 2020b).

The cyclic nature of the supply and demand for specific metals whose production is extremely concentrated in geographic terms and controlled, and where society cannot solely rely on ore mining (Kirchherr et al., 2017) makes sticking to circular economy principles, such as effective recycling and processing of secondary sources, a must (Tunsu et al., 2019). Mine tailings are now seen as a potential source of several metals and minerals (Binnemans et al., 2015; Tunsu et al., 2019). The valorization of mine tailings is at an early stage of research; there is a lack of technology that would enable transferring knowledge from the laboratory scale to an industrial level (Kinnunen and Kaksonen, 2019).

Economic gains from the recovery of CRMs come with the added benefits of reducing the volume of mine waste. Additional benefits can be achieved if, as a result of the processing of mine tailings, these can be chemically and physically stabilized, reducing the costs of mine closure by decreasing environmental impact and health consequences. A significant advantage is to recover water for mining reuse from mine tailings while reducing its reliance on seawater (Cisternas and Gálvez, 2018; Ramírez et al., 2017). Another essential factor is decreasing energy consumption and greenhouse gas emissions involved in pumping seawater to high altitudes for hyperarid locations, where mining companies are located

(Araya et al., 2018; Ramírez et al., 2019). It is also essential to notice that obtaining CRMs from mine tailings reduces the processing of comminution stages (Falagán et al., 2017), minimizing energy consumption and greenhouse gas emissions. Notably, greenhouse gas emissions can vary for every CRM, e.g., in the case of phosphorus the greenhouse gas emissions rise gradually in the mining phase and increase exponentially in the recycling stage (Rahimpour Golroudbary et al., 2019b); in the case of niobium, mining represents 21% of greenhouse gas emissions, 72% are generated in the production stage and recycling from scrap accounts for only 7% (Rahimpour Golroudbary et al., 2019c); on the other hand, recycling of lithium from lithium-ion batteries generates greenhouse gas emissions by 16-20% higher than its primary production (Rahimpour Golroudbary et al., 2019a).

The results show that tailing storage facilities of copper mines in Chile contain significant quantities of CRMs and, depending on the price, some of them could be extracted. Therefore, the early evaluation of the project's profitability and feasibility to recover CRMs from mine tailings help in finding alternatives, and considering the flexibility given by real options, even to postpone the investment until the technology development allows to re-process the tailings. Additionally, it represents a secondary source of CRMs, decreasing the dependence on reserve extraction (El Wali et al., 2019).

The analysis made on the in-situ value of TSFs of active tailings of northern Chile shows that they contain considerable quantities of several critical metals such as REEs, vanadium, cobalt, silicon metal and scandium. The advantages of mine tailings re-processing include the recovery of desirable metals in one location, ensuring land reclamation, reduction of landfill areas, diminishing the concentration of harmful compounds, and no need to open new mines (Binnemans et al., 2013; Farjana et al., 2019; Ganguli and Cook, 2018).

Since mine tailings have been already part-processed, by comminution, the costs, both CAPEX and OPEX, of extracting metals from tailings could be attractive in comparison to the development of a new project, based on primary ores (Falagán et al., 2017). Moreover, the use of secondary sources could help mitigate the depletion of natural resources (Alwaeli, 2011a). For the data used, the result of the DCF method is a negative outcome of the NPV which suggests that the investment should not be considered at the moment. The results of the sensitivity and uncertainty analysis show that CAPEX has a greater influence than the other studied variables. Therefore, it is justified to develop processes and technologies that enable lower capital expenses. If time is a variable in an investment project, then time and CAPEX are both variables with greater influence. It can also happen that the cost of secondary materials is lower, but the cost of processing is higher because of additional treatments or due to lower capacity (Alwaeli, 2011b).

ROA brings in additional value, so decision-makers can explore alternatives while waiting to invest or decide to abandon a project. While waiting for the uncertainty to clear off, to re-estimate the project payoff (Arnold, 2014; Kodukula and Papudesu, 2006). If the payoff continues to be unfavorable, the decision may be to keep waiting; otherwise, if the conditions to invest in scandium production from mine tailings are favorable with a high expected payoff, the decision would be to invest. ROA calculations are a supplement to traditional valuation methods such as DCF based NPV (Brandão and Dyer, 2005; Kodukula and Papudesu, 2006).

ROA is usually framed in shorter periods than the ones used for long term investments (Kodukula and Papudesu, 2006), in this study five and ten-year time horizons were used to frame the project; for both periods, NPV is negative, but if the uncertainty clears out, the project may be feasible. Framing the investment in a longer period, such as ten years, but not as long as twenty years, allows decision-makers to wait to invest in a project when investment can be regained.

The methodology presented in this study was validated using copper tailings of northern Chile as a case study. The geochemical content of tailings may vary from one geographical area to another depending on the type of mineral deposits. In consequence, the content of the valuable elements will be different depending on the mine tailing analyzed. The geochemical results of mine tailings analysis are essential to perform profitability analysis of their re-processing.

On the limitations of the study, it considers only the economic aspect of valorization of the project to obtain CRMs from mine tailings. However, it should be mentioned that the valorization of tailings may be profitable in most cases if environmental, social and safety factors are considered, e.g. chemical and physical stabilization, land reclamation, social license to operate. As was previously stated by Kinnunen and Kaksonen (2019) technology development is still much needed to add value to mine tailings. Therefore, a multidisciplinary approach is imperative to develop projects based on re-processing mine tailings. Future research should include the assessment of the environmental impact of the re-processing of mine tailings, as they can contain heavy metals that could be scattered during the process. Some tailings deposits in Chile need urgent intervention due to the presence of one or more heavy metals (Lam et al., 2020a). Because, at the moment, the economic assessment does not justify the recovery of CRMs, a comprehensive solution to the problem of tailings should be applied. The valorization of tailings could include not only recovering of valuable elements, but also carbon capture from tailings, as it has been suggested in some studies (Azadi et al., 2019; Li et al., 2018), and use of tailings as construction material (Lam et al., 2020b; Solismaa et al., 2018).

6. Conclusions

Mine tailings need to be adequately stored; otherwise, they can lead to massive catastrophes that can affect human settlements and the ecosystem inflicting irreparable damage. Proper mine tailings management includes their chemical and physical stabilization; however, resource recovery can also add profitability to the last stage of mine closure. Moreover, the re-processing of wastes contributes to limiting the number of new mining projects based on virgin resources, which usually have a considerable environmental impact. The assessment of the economic potential of wastes is a crucial activity facilitating the implementation of the circular economy principles.

The mine tailings deposits have usually lower concentrations of CRMs than ore mines. However, the mine tailings are an attractive alternative for exploitation as they are stored in deposits with large volumes and hence, having a considerable potential for the production of CRMs. The additional factor is the fact that tailings have been already pre-processed, e.g. in comminution processes. The case study features Chilean copper mine tailings, to analyze the ones with significant volume among the 740 tailing storage facilities present in the country. Mine tailings deposits that are currently active were analyzed, using geochemical content information provided by The National Service of Geology and Mining (SERNAGEOMIN). These deposits contain important quantities of rare earths elements, cobalt, vanadium, silicon, and barium. Therefore, these copper mine tailings could have substantial economic potential as secondary sources to obtain CRMs. It is well-known that some CRMs are more economically attractive than others, due to their high market price. Therefore, the demand, supply risk and economic importance of each CRM should be considered when analyzing the profitability of mine tailings re-processing.

In this study, a novel approach to assess the profitability of mine tailings to obtain CRM is introduced. A framework that includes ROA, sensitivity and uncertainty analysis is proposed, which allows for adding flexibility, contrary to traditional valuations tools. DCF and ROA were applied to analyze the feasibility of producing scandium by re-processing the tailing deposits featured in the case study. Additionally, sensitivity and uncertainty analysis was performed to study the influence of the price of the commodity, CAPEX, OPEX, and discount rate. These evaluations were used as a complement to the DCF and they include Monte Carlo simulation of the NPV and the representation of the results as boxplot and Sobol´ indices.

The DCF method showed a negative NPV for investments of 5 and 10 years. The results of the sensitivity and uncertainty analysis indicate that CAPEX has a greater influence on NPV. ROA adds flexibility and the possibility, as an alternative, to choose to wait until the uncertainty is reduced. Based on the calculations, it is concluded that using a real options approach to analyze an investment for the production of CRMs from mine tailings is a useful instrument, considering the high uncertainties in the market and the development of process technology.

To summarize, the main conclusions of this study are following:

- One can state that the analyzed mine tailings have substantial economic potential to be re-processed to obtain some CRMs. The assessment is based on the quantity and actual price of specific critical materials.

-The basic evaluation tool used, DCF, gives a negative value to the investment based on re-processing of tailings to obtain scandium.

-Sensitivity and uncertainty analysis show that CAPEX and time to invest, either to invest in year 0 or to wait to invest until year 10, have more impact on the outcome of the NPV than OPEX, price, and production volume. Therefore, one can conclude that technology development is much needed to improve processes and technologies of mine tailings re-processing to recover valuable elements.

- Based on the calculations, it is concluded that using a real options approach to analyze an investment for the production of CRMs from mine tailings is a useful alternative, considering the uncertainties in the market and the development of process technology.

The novelty of this article relies on including risk and uncertainty in the evaluation of re-processing of mine tailings projects. The proposed approach enables flexible assessment of investment decisions. When traditional methods, such as the DCF method, indicate that a project is not economically attractive, a ROA reevaluates the project by considering options such as wait until the project is economically feasible. The option of waiting is an interesting alternative in the case of resource valorization of mine tailings. It is due to the lack of technological development and economic business models for treating mine tailings as a source of CRMs. Therefore, more research on these aspects is still needed.

Mine tailings as a secondary source for obtaining valuable elements is still a novel option that needs to be developed on an industrial scale. Therefore, there are many opportunities for improvement that may eventually lead to the successful valorization of mining waste. A multidisciplinary approach is essential to secure the success of re-processing of mine tailings to obtain CRMs.

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