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Multi-Criteria Analysis for Circular Economy Promotion in the Management of Tailings Dams: A Case Study

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Abstract: Copper ore is a non-renewable resource with lower ore grades, which means that the extraction of more rock material is required to produce the same amount of copper, implying a greater consumption of materials, reagents, water, and energy. Since there is a greater amount of copper sulfide present in nature, concentration using the bubble flotation method will generate a greater number of tailings. This article discusses the environmental issues resulting from tailings dams and how multi-criteria decision analysis can help prioritize those sites in order to promote circular economy measures to compensate for and reduce the impacts of this type of waste generated by the copper mining industry. This work aims to contribute to this purpose by taking information from abandoned and non-active tailings, which are currently present as a result of the lack of regulations in times prior to environmental obligations and because they are metallurgical waste from old operations that had metal recovery rates that were much lower than the current rates. We propose a model based on the multi-criteria Promethee method to prioritize the tailings dams according to the commercial value of the existing materials in the deposits. A case study with an application of the model to 103 dams in the mining region of Coquimbo in northern Chile is shown.

Keywords: tailings dams; circular economy; multi-criteria decision making; Promethee

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1. Introduction

Copper is mainly found in nature as copper oxide and copper sulfide, the latter being the most abundant. Most of the world's copper mines are present in Chile, Australia, Peru, China, the US, and Mexico [1], with Chilean production being responsible for almost one-third of the world's copper production [2].

Commercially exploited copper sulfide metallic ores first undergo a comminution process until they reach a very fine size of less than 0.5 mm. They are then processed using bubble flotation; it is in this process that waste products called "tailings" are produced. These tailings are the parts of the mineral that are discarded because they do not have economic value for the mining company. In the case of Chile, more than 95% of the ore processed becomes tailings. It is estimated that by 2035, the generation of tailings will be 3.25 times the quantity generated in 2015 [3].

Tailings contain variable amounts of different elements that can cause damage to human health and the environment [4]; this includes arsenic, cadmium, mercury, and others. The author of [4], moreover, notes that "The risk of harm can be even higher for mining waste, ore processing tailings or metallurgical residues from older operations, as metal recovery rates were generally quite lower than modern operations."

The copper production process begins with extraction, during which the copper can be present in different mineralogical species. Oxidized and sulfide minerals are the most commonly processed species. Copper sulfides are increasingly abundant, while copper oxides, which are processed by hydrometallurgy, are increasingly scarce, decreasing from 30.8% in 2015 to a projected 12.0% in 2027 [5]. After extraction, both types of minerals must undergo a crushing process using crushers. However, in the case of sulfide minerals, after being crushed, they must be sent to the grinding stage before they are able to enter the process of mineral concentration. This last process takes advantage of the buoyant properties of copper minerals after they are incorporated into a series of chemical reagents and water. Froth flotation is one of the most important and widespread concentration methods. It is based on the exploitation of the differential properties of valuable and gangue minerals, also known as wettability [6]. This process is carried out in flotation cells or tank reactors that are agitated by air bubbles injected into the pulp. Foam (which is hydrophobic) forms on the surface and is collected as a concentrate rich in copper ore; the pulp from this process feeds the next cell, and so on. Finally, the discards from this process, called "tailings", are transported to a tank far from the facilities. These dams are built in uninhabited areas which are close to the mine and take advantage of the geography of the area.

1.1. Risks Involving Tailings Dams

Tailings deposits are a form of mining waste collection that have generated the most problems for the mining industry [7]. In order to point out the impacts that have occurred due to catastrophes originating from tailings dam failures, a brief description of these events is presented. The WISE Uranium Project database [8] presents a chronology of the main tailings dam failures in the world from 1961 to January 2023 (the date of the literature review). This organization notes that the availability of data is limited because the compilation is not complete; however, according to the evaluation made by the authors when cross-checking information with local sources, this information is reliable, reporting data such as date, location, company involved, type of mineral, type of incident, amount released, and impacts of dam failures. In the case of Chile, ten incidents involving copper ore were recorded during this period. From the most recent to the oldest, the first incident occurred in 2016, in the town of Ujina, Pica, Tamarugal Province, Tarapacá Region, in which 4500 cubic meters of tailings were spilled. The incident was caused by a rupture in a tailings transport chute. As a result, the material flowed toward an ancestral grazing area, threatening four vicuña specimens and a protected camelid species and ultimately reaching the groundwater. Since 2016, there have been no incidents in the country, which is a sign of the success of the regulations enacted by authorities in the last decade, together with the public and private sectors comprising the mining industry. The second episode was in 2003, in the town of Cerro Negro, Petorca Province, Valparaíso Region, which involved a failure of a tailings dam that spilled 50,000 tons of tailings; the material flowed 20 km downstream in the La Ligua river. The third and fourth episodes took place in 1985, located in Veta de Agua No. 1 and Cerro Negro No. 4. The first event occurred due to the failure of a dam wall, which was caused by liquefaction during an earthquake in 1985 and discharged 280,000 cubic meters. The tailings flowed five kilometers downstream. The second event also occurred due to the failure of a dam wall that was caused by liquefaction during the earthquake. In this event, 500,000 cubic meters of waste were released, and the tailings flowed eight kilometers downstream. Previously, another six episodes of spills occurred in 1965, in locations such as Bellavista, Cerro Negro No. 3, Cobre Nueva Dam, Cobre Vieja Dam, Nueva Patagua Dam, and Los Maquis. All these dam failures occurred during an earthquake that occurred that year. These six episodes, which were all specified as resulting from liquefaction, spilled 70,000, 85,000, 350,000, 1.9 million, 35,000, and 21,000 cubic meters, respectively. The tailings flowed 800 m, 5 km, 12 km (destroying the town of El Cobre and killing more than 200 people), 5 km, and 5 km in the first, second, third, fifth, and sixth cases, respectively; the fourth case lacks information. These catastrophes occurred due to various factors, including operational causes, material fatigue, and earthquakes, among others.

Despite the fact that a given landfill may be well-designed and may have approval from the relevant agencies, or the fact that tailings storage areas are considered to be "low-risk facilities", it does not mean that such facilities can withstand inadequate management or operation over time. In [9], the author mentions that "Risk assessments must be carried out before operations begin, and then periodically updated to duly eliminate all failures or deficiencies that may have occurred during construction or operation, in order to prevent potential accidents from occurring in an early stage". In [10], the authors discuss the causes of tailings dam failures, including seepage, foundation failure, overflow, and earthquakes, and provide a reference for tailings dam design and construction in order to reduce the occurrence of negative risks. The investments necessary to protect the environment and human health will be rewarded by avoiding the possible costs of remediating the consequences of accidents, which could be many times higher than the initial investment [11]. Moreover, disasters may occur in sites cataloged as being "abandoned" and left in a worse condition, as was the case in the town of Chañaral, Chile, in March 2015 [12], in which an alluvium-carrying material from abandoned tailings swept away the town. During the investigation [13], the worrying situation in Chile was pointed out with respect to the abandonment of tailings fills due to the lack of environmental regulations prior to the enaction of the law on general environmental bases in 1930. These authors of [13] indicate that waste was discharged into the soil, rivers, and seas for decades, thus pointing out the consequences of contamination on human health and the environment for several generations.

The Ministry of Mining of Chile supervises the public "National Geology and Mining Service", known as SERNAGEOMIN, whose mission is to be a "technical body in charge of generating, maintaining and disseminating information on basic geology and resources and hazards geology of the national territory, for the well-being of the community and at the service of the country, and to regulate and/or supervise compliance with mining regulations in terms of safety, property and closure plans, to contribute to the development of national mining" [14]. This service, in addition to other high-level organizations related to environmental regulations, such as the Ministry of the Environment (MMA), the Superintendence of the Environment (SMA), and the Environmental Evaluation Service (SEA), among others, provide the country with a system of government in environmental matters at the national level. In 2018, the Ministry of Mining announced a series of measures to provide security and information to the communities that are close to the presence of tailings dams. These tailings storage facilities can be classified as active tailings, inactive tailings, or abandoned. According to SERNAGEOMIN, "active tailings deposits" are those that have a known owner and are in an operating condition; those classified as "inactive" are deposits with known owners but are not currently being exploited and are still without legal closure; and those classified as "abandoned" are deposits that are not in operation and have an unknown owner or resolution of origin.

Chile ranks first in the world in copper production, with 5,588,084 fine metric tons produced during 2021, which is equivalent to 26.6% of the world's production [7]. Ore processing capacity, both in concentration and leaching, is concentrated in the center and north of the country, mainly in the Antofagasta Region, with 35% of the flotation capacity and 75% of the national leaching capacity [5]. As shown in Table 1, the largest amounts of tailings deposits are found in the Coquimbo and Atacama Regions, which are directly linked to sites with many scattered deposits, although this does not necessarily imply a greater mass of waste material.

After the disaster of the dam collapse in the town of Brumadinho, Brazil, which occurred on 25 January 2019, many countries became aware of the need to review their status to help prevent catastrophes. Chile was no stranger to this scenario, and in response, the government accelerated the announcement of the National Tailings Deposits Plan policy. This policy is based on three pillars: the safety of people, the protection of the environment, and the circular economy and innovation. In addition, a pilot plan for the direct monitoring of tailings dams and emergency management measures was initiated; the Ministry of Mining indicated that "this (policy) will have a direct relationship with SERNAGEOMIN and in turn with ONEMI (National Emergency Office), so that, as in the case of tsunami alerts, people downriver receive an alert to the cell phone in case of emergency to evacuate the area that could be affected" [15]. As of 1 January 2023, ONEMI was transformed into the new National Disaster Prevention and Response Service (SENAPRED), an entity that will have the responsibility of advising, coordinating, organizing, planning, and supervising the activities related to Disaster Risk Management in the country.

Table 1. Regional distribution and state of tailings deposits (2021).

Region	Active	Not Active	Abandoned	Total
Tarapacá	2	0	6	8
Antofagasta	12	24	16	52
Atacama	31	113	23	173 *
Coquimbo	39	244	106	389
Valparaíso	14	55	11	80
Metropolitan	6	14	6	26
O'Higgins	3	15	1	19
Maule	4	2	0	6
Aysén	0	5	4	9
TOTAL	111	472	173	762 *

Source: [7] (* Add six under construction).

1.2. Possible Use of Tailings Deposits

Mining is a fundamental industry for the development of modern society, but it is also the largest producer of waste in the world [16]. There has been an increase in concentration processes, which means a growth in the amount of tailings produced since copper grades are decreasing; this, in turn, means processing a greater quantity of material in order to obtain the same amount of copper production, implying a greater amount of tailings as well. Sulfide residues usually represent between 80 and 98% of the weight and between 150 and 170% of the volume of the extracted ore [17], as most of the metallic ores are processed using foam in the flotation process. The copper concentration in flotation tailings is reported to be relatively high, especially in northern Chile [2]. It must also be added that the costs of the process of obtaining the copper concentrate represent 77% of the total cost [18]. An opportunity to use tailings is presented in [19], in which it is stated that the cost of extracting residual metals from waste can be more economically attractive than extracting it from a deep deposit. The authors present an experimental study in a copper mine in Las Cruces, Spain, which produces more than 1.5 million tons of mineral waste each year. An extraction rate of copper of up to an 85% (the maximum reached in bioleaching tests) could be reached using a bioleaching technique. They report that with that amount of waste, they could produce 9.2 kilotons of metal (with a value of ~USD 44 million as of 2016). Additional revenue could come from zinc, which could also be recovered by bioleaching (~USD 1.3 million per year). They also mention how much silver could be potentially extracted and recovered, although more research is needed for exploitation at an industrial scale. This study suggests that chemical extraction is a feasible option, but that the copper bioleaching process produces a mineral residue that is poor in silver. In these experiments, an efficient extraction (>90%) was achieved by bioleaching, and the authors state that the estimated total value of the copper that could be extracted and recovered from old waste using this method ranges from USD 225 to 337 million. Again, bioleaching and zinc recovery would have additional value (estimated at USD 30–45 million) [19]. The production of tailings is expected to increase in coming years due to the intensive mining of low-grade copper ores [20]. This study contributes to the promotion of a circular economy in abandoned and inactive tailings, demonstrating in a novel way the use of multi-criteria decision models which could be applied to any similar case, with a particular application to the Coquimbo region in Northern Chile.

2. Materials and Methods

This case study was developed using public databases maintained by SERNAGEOMIN [21], which serves the national government of Chile by providing data for strategic programs related to the recovery of valuables in tailings deposits. The study was developed through an iterative data collection process by compiling databases shared by the Ministry of Mining, providing general data on tailings deposits such as the location, area, and estimated content of recoverable materials.

Initial activities focused on the data analysis of variables associated with tailings dams, such as coordinates, current volume, authorized volume, and the characterization of their current chemical composition. The case study was developed with 103 tailings dams located in the Coquimbo Region out of a total of 389 deposits in the region and 762 in the country. This number was determined based on the completeness of the database, as many sites did not have sufficient data.

From an engineering perspective, the proposed approach is to install reclamation plants near the sites at which the tailings dams are located. The location of such plants will depend on the costs of production, transportation, and mitigation measures, as well as the equally important consideration of the potential commercial value of the materials that could be recovered from these facilities. Recent work [22] discusses the potential value of materials used in modern industries (electric mobility, electronics, wind mills, etc.), which will provide the basis for deeper economic evaluations. The work presented here is a first step in identifying the best candidates for feasibility studies. However, due to the availability of data, the model considered in this article only addresses the mass of selected elements, leaving other aspects, such as the socioeconomic impacts [22] on nearby settlements, for future work.

The work presented in this article deals with the prioritization of tailings deposits for intervention planning with economic purpose. However, it should be noted that this research is part of a more holistic approach. This approach proposes a hierarchical method that is divided into three sequential phases. Phase 1 deals with the model for prioritizing tailings dams (proposed in this work), and Phases 2 and 3 address the locations of the plants in relation to the storage facilities. Due to the large number of nodes, Phases 2 and 3 employ data mining techniques that use the k-medoids and k-means clustering algorithms, respectively. The results and details about the location algorithms, k-medoids and k-means, are reported in previous work by [23,24]. This paper explains Phase 1 in the application of a multicriteria decision-making model that is solved by the Promethee method. Figure 1 shows the types of results of the three phases. On the left, the figure shows the most attractive dams for commercial value in a darker color; in the center, clusters by localities are shown in different infilled colors; finally, on the right, the hub location for each cluster is shown in cyan circles. The connection between Phase 1 on one hand and Phases 2 and 3 on the other is that the distances used in the data mining methods are weighted by the scaled weights obtained from the Phase 1 multi-criteria model.

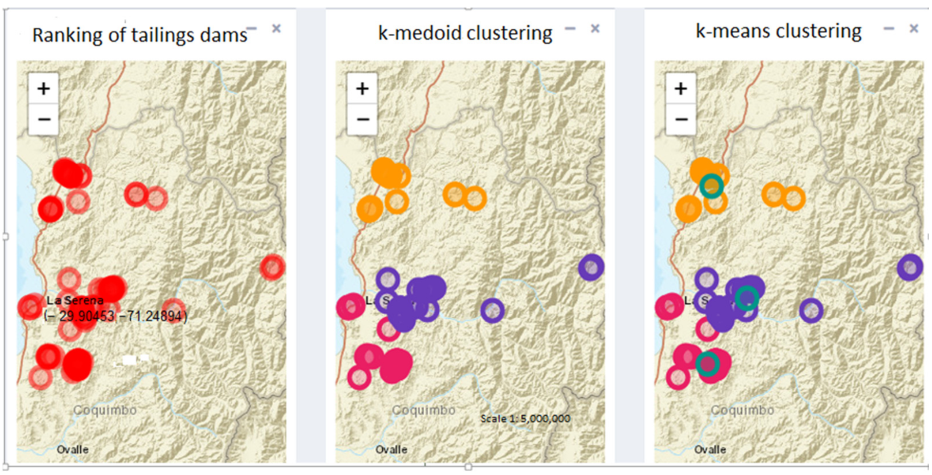

Figure 1. Graphic solutions obtained from the three phases.

3. Results

Today, despite being safely confined, the fundamental problem with tailings dams continues to be the possible failure over time of the protective measures for the management of mine waste. As can be seen in previous cases, the mismanagement of tailings can have enormous consequences in terms of human disasters and/or environmental damage, generating legal, social, and economic responsibilities for mining companies and their owners.

In 2018, the Chilean Ministry of Mining [25] announced different measures to promote the remediation and reprocessing of abandoned mining sites. The tailings remediation policy consists of a series of measures for which the objectives are to secure abandoned mining sites and mediate the early resolution of conflicts between companies and communities. Broadly speaking, this policy seeks to address a historical debt, such as the remediation of environmental liabilities for mining, which implies, among other aspects, their reuse and closure, ensuring their physical and chemical stability. According to the organization, the task is ambitious, and the challenge is shared among the actors, calling for the joint efforts of the government, private companies, academia, and NGOs.

The measures contemplated in the tailings dam plan are oriented on two fronts: (1) active tailings and (2) abandoned and inactive tailings. For the assets, the main management instrument will be the implementation of the tailings dam program at the national level in a gradual and standardized manner, according to the category of the mining company. This program includes the real-time monitoring of tailings, which, in turn, can be followed online by all citizens. Regarding inactive tailings, various management instruments have been contemplated, such as their remediation, using the Environmental Impact Assessment System as a means to offset the impacts associated with mining activity. Another example is the use of technologies to reuse these tailings and convert them into construction materials (the circular economy approach), as well as the use of other minerals of commercial value. The aim is to carry out the process in a participatory manner so that the program works as an "ideas bank", with the objective of grouping the best ideas on how to ensure the safety of a tailings dam or the best technologies for its reprocessing.

A safe, fair, and sustainable mining industry in which mining waste is used as raw material is consistent with the principles of a circular economy [17]. The full use of such volumes of tailings as feedstock is difficult to achieve: a copper mine that processes 20 kT/d of ore with 0.5% Cu discharges 19.6 kT/d of tailings, which occupy a volume of 14.4 km^3/d on the surface and consume 10 ha/year for a 50 m deep dam [17]. Tailings reprocessing can be a promising alternative to recover critical and valuable metals in addition to copper [2].

In summary, it is quite a challenge to consider tailings as potential resources. In [19], it is pointed out that mine tailings can also be recycled and reused. Different examples of scientific literature indicate different alternatives of use for this type of waste, which is characterized geometallurgically [26]. Potential alternatives include using tailings to improve the properties of concrete [27], to obtain critical raw materials [28], to obtain lime and CO2 [17], and to assist in the manufacturing of brick and other building materials [29], among others.

Mining waste varies according to its physical and chemical composition, the type of extraction, and the way in which the mineral is processed. The mining industry reports an annual processing of millions of tons of mineral of which more than 95% are eliminated in the form of waste rocks and mining residues [19]. Tests performed with phytomining for the management of tailings from artisanal gold mines were carried out in Indonesia a few years ago. These tests achieved a sequence that captured the precious metal [30]. The authors of [19] developed a protocol for mineral leaching and metal recovery in two stages, extracting copper from the sterile generated as waste material in two mines in Spain and Serbia. In Krugersdorp, a mining town in South Africa described as having significant levels of potentially harmful elements from old dams and tailings dumps, a field experiment is being carried out to assess the relevance of the re-exploitation of old dams and spillways [31]. Pan African Resources reports on its website that at the end of 2024, it will begin its production of tailings retreatment plants, confirming the economic value of such retreatment and noting that it is one of the few opportunities for the retreatment of tailings from the large-scale gold mines left in South Africa [32].

The purpose of this study is to be able to advance the task and pave the way toward more sustainable mining. In this context, the present work aims to contribute to this purpose by proposing a model that prioritizes tailings dams according to the commercial value of existing materials in the deposits. Commercial values are addressed in a general way, according to [33,34].

3.1. Use of Promethee and Software

In Phase 1, the 103 dams classified as "non-active" or "abandoned" were prioritized using the Promethee method [35,36]. This method has been widely used in many studies and has undergone several improvements and extensions [37]. The experiments were carried out using the academic version of the Visual Promethee™ software. Six criteria were considered in this phase. The top five included the concentration (in grams per ton, g/t) of copper (Cu), zinc (Zn), barium (Ba), lead (Pb), and vanadium (V). The sixth variable was the current mass of tailings deposited in the dams (in tons). Although about 30 more elements and many compounds may be present in the deposits, these five elements were considered the most important for the pilot experiments, leaving the analysis of other elements for future work.

3.2. Description of Scenarios

Table 2 shows the settings for the experiments. As mentioned above, the criteria were the concentrations of elements and the total mass of tailings in the 103 tailings dams. Scenario 1 was run to compare the software with a Python language implementation of Promethee that only provided flow computations but integrated with the Phase two and Phase three data mining algorithms in a computing environment implemented by R-Studio™. The classification was the same, but the following scenarios were run on the Visual Promethee™ software due to its features for performing various analyses. Linear preference functions were chosen as parameters, with the minimum and maximum values of each variable as levels of indifference and preference, respectively. In Scenario 3, the weights were changed, and in Scenario 4, the mass variable was deactivated since many dams did not have this variable updated and its values were zero, which skewed the ranking.

Table 2. Scenario settings.

Active	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Actions (Dams)	103	103	103	103
Variables	6	6	6	5
Weight Cu	1	1	4	4
Weight Zn	1	1	2	2
Weight Ba	1	1	1	1
Weight Pb	1	1	2	2
Weight V	1	1	9	9
Weight Mass	1	1	7	0
Preference function	Usual	Linear	Linear	Linear

Table 3 shows a sample of the data for the first 30 actions (the total is 103). In the mass variable, the zero values were not available in the source database; therefore, in Scenario 4, this variable was deactivated to study the effect on the ranking. Table 4 shows the levels of indifference and preference for Scenarios 2–4 for linear functions and 103 deposits.

Table 3. Active Scenario 2 evaluations (sample of first 30 actions).

Action.	Cu (g/t)	Zn (g/t)	Ba (g/t)	Pb (g/t)	V (g/t)	Mass (t)
Dam-01	0.00	0.00	0.00	0.00	0.00	0.00
Dam-02	1329.00	5703.00	2591.00	1189.00	103.00	0.00
Dam-03	1329.00	5703.00	2591.00	1189.00	103.00	0.00
Dam-04	328.00	182.00	2369.00	90.00	194.00	0.00
Dam-05	220.00	5.00	394.00	307.00	124.00	0.00
Dam-06	0.00	0.00	0.00	0.00	0.00	0.00
Dam-07	0.00	0.00	0.00	0.00	0.00	0.00
Dam-08	328.00	182.00	2369.00	90.00	194.00	0.00
Dam-09	5980.00	2182.00	456.00	852.00	79.00	0.00
Dam-10	41.00	79.00	585.00	38.00	124.00	0.00
Dam-11	5113.00	119.00	471.00	43.00	128.00	0.00
Dam-12	328.00	182.00	2369.00	90.00	194.00	0.00
Dam-13	220.00	5.00	394.00	307.00	124.00	0.00
Dam-14	0.00	0.00	0.00	0.00	0.00	0.00
Dam-15	191.00	1493.00	2015.00	199.00	142.00	0.00
Dam-16	220.00	5.00	394.00	307.00	124.00	0.00
Dam-17	328.00	182.00	2369.00	90.00	194.00	0.00
Dam-18	191.00	1493.00	2015.00	199.00	142.00	0.00
Dam-19	220.00	5.00	394.00	852.00	124.00	0.00
Dam-20	5980.00	2182.00	456.00	90.00	79.00	0.00
Dam-21	328.00	182.00	2369.00	0.00	194.00	0.00
Dam-22	0.00	0.00	0.00	852.00	0.00	0.00
Dam-23	5980.00	2182.00	456.00	0.00	79.00	121,704.00
Dam-24	0.00	0.00	0.00	1189.00	0.00	0.00
Dam-25	1329.00	5703.00	2591.00	165.00	103.00	33,278.00
Dam-26	5810.00	57.00	20.00	852.00	124.00	0.00
Dam-27	5980.00	2182.00	456.00	0.00	79.00	0.00
Dam-28	0.00	0.00	0.00	0.00	0.00	0.00
Dam-29	0.00	0.00	0.00	307.00	0.00	0.00
Dam-30	220.00	5.00	394.00	38.00	124.00	0.00

Table 4. Preference parameters for Scenario 2–3–4.

Criteria	Cu	Zn	Ba	Pb	V	Mass
Min/Max	Max	Max	Max	Max	Max	Max
Preference Fn.	Linear	Linear	Linear	Linear	Linear	Linear
Thresholds	Absolute	Absolute	Absolute	Absolute	Absolute	Absolute
Indifference	0.00	0.00	0.00	0.00	0.00	0.00
Preference	5980.00	5703.00	12,996.00	1189.00	204.00	97,387,379.00

In Appendix A, Table A1 shows the ranking by flow value (Phi) for the top 40 positions for each scenario, and Table A2 shows a comparison of the position for the different scenarios.

4. Discussion

As can be seen in Appendix A, Table A1, the rankings for Scenarios 1 and 2 for the top 40 positions do not differ much, and most tailings dams agree. Remember that the difference between both scenarios is that Scenario 1 uses the Usual preference function and Scenario 2 uses the Linear preference. That is, there would be a relative robustness of the ranking in terms of the type of preference. Tables A2 and A3 of Appendix A show the top twenty and bottom twenty positions in Scenario 2, respectively; remember that in Scenario 2, all criteria have the same weight as value one.

Although it is a very small sample to deduce the statistical behavior of the model, a certain coincidence can be seen between Scenarios 1, 2, and 3. This is shown by the mean square error (ECM) of the first 20 ranking positions and their average. It can be seen that there is much more coincidence in the last 20 positions (Table A3) in which the less attractive options coincide. This can be explained by the low values in all the variables.

In Scenario 3, with the same linear functions, the ranking differs considerably for the first positions, meaning that the decision is sensitive to the weights except for the less attractive actions in which the flows are negative due to the relative lack of data, often with little or no levels.

Scenario 4 differs from Scenario 3 in that the mass variable was turned off due to many missing or zero values. However, in this case, the results of Scenarios 4 and 3 are very similar, as can be seen in Tables A2 and A3 of Appendix A.

5. Conclusions

In this work, a method was provided to classify tailings dams according to the content of the remaining materials with economic utility, such as Cu, Zn, Ba, Pb, and V. The Promethee method was used as a strategic tool for making decisions.

Considering six criteria, the first five included the concentrations (in grams per ton, g/t) of copper (Cu), zinc (Zn), barium (Ba), lead (Pb), and vanadium (V), and the sixth variable was the current mass (in tons) of tailings deposited in the dams. Complex real-world problems, such as those related to the intricacies of balancing environmental objectives with industrial developments, require powerful tools for prioritization due to the large amount of data and decision variables, the multiple interrelationships between variables and criteria for public planning that are often in conflict, and the methods used as an aid for decision making. The results of the models must provide reliable information to guide public policy and direct private companies about where to invest their efforts when considering sustainable production models in such a way that the models contribute to the balance of economic, environmental, and social issues, employing this methodology as support in different scenarios.

This case study was oriented to dams classified as "inactive" or "abandoned" in Northern Chile, where it can be extended to other types of classification. SERNAGEOMIN [7] has estimated that, in Chile, current mining operations generate tailings at a rate of 530 million tons per year, adding that they cover extensive areas and have accumulated, to date, approximately 24 billion tons in the territory of Chile (calculated from the current National Registry of Tailings Deposits).

Therefore, there are challenges for future research in favor of promoting the circular economy to obtain critical raw materials, not only in the processing of copper sulfide minerals but also in the processing of other types of minerals beyond copper that also result in waste tailings. Additionally, the probability of accidents occurring due to failures in tailings dams is always present, whether due to anthropogenic or natural conditions. Therefore, viewing this problem as an opportunity to move toward the circular economy in the management of tailings dams, it is appropriate to carry out favorable actions with this type of waste. This includes favoring not only the environment and the health and life of people but also economic factors, including the costs of mitigating and remedying the consequences of accidents and the extraction of commercially valuable and useful minerals. Although the model presented in this paper was developed for the pre-established configuration of the case study, the decision criteria and parameters considered can be adapted to other cases to broaden the analysis. This case study demonstrates the feasibility of applying multi-criteria decision-making techniques to the progressive analysis of the impact of tailings deposits. In future research, the analysis may be extended to other criteria related to sustainability issues, such as the location of human settlements and water pollution.

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Appendix A

Table A1. Ranking by phi (net flow) value of the top 40 positions of each scenario.

Rank.	Sc.1	Sc.1	Sc.2	Sc.2	Sc.3	Sc.3	Sc.4	Sc.4
	Action	Phi	Action	Phi	Action	Phi	Action	Phi
1	Dam-25	0.4297	Dam-02	0.2194	Dam-39	0.2763	Dam-80	0.2221
2	Dam-02	0.402	Dam-03	0.2194	Dam-80	0.1568	Dam-26	0.1864
3	Dam-03	0.402	Dam-52	0.2194	Dam-26	0.1311	Dam-09	0.125
4	Dam-52	0.402	Dam-57	0.2194	Dam-44	0.0907	Dam-42	0.125
5	Dam-57	0.402	Dam-73	0.2194	Dam-66	0.0871	Dam-43	0.125
6	Dam-73	0.402	Dam-74	0.2194	Dam-85	0.0869	Dam-44	0.125
7	Dam-74	0.402	Dam-75	0.2194	Dam-9	0.0869	Dam-45	0.125
8	Dam-75	0.402	Dam-81	0.2194	Dam-42	0.0869	Dam-54	0.125
9	Dam-81	0.402	Dam-82	0.2194	Dam-43	0.0869	Dam-66	0.125
10	Dam-82	0.402	Dam-86	0.2194	Dam-45	0.0869	Dam-67	0.125
11	Dam-86	0.402	Dam-88	0.2194	Dam-54	0.0869	Dam-68	0.125
12	Dam-88	0.402	Dam-89	0.2194	Dam-67	0.0869	Dam-71	0.125
13	Dam-89	0.402	Dam-90	0.2194	Dam-68	0.0869	Dam-72	0.125
14	Dam-90	0.402	Dam-91	0.2194	Dam-71	0.0869	Dam-83	0.125
15	Dam-91	0.402	Dam-95	0.2194	Dam-72	0.0869	Dam-84	0.125
16	Dam-95	0.402	Dam-96	0.2194	Dam-83	0.0869	Dam-85	0.125
17	Dam-96	0.402	Dam-97	0.2194	Dam-84	0.0869	Dam-59	0.1215
18	Dam-97	0.402	Dam-98	0.2194	Dam-59	0.0844	Dam-02	0.1202
19	Dam-98	0.402	Dam-99	0.2194	Dam-02	0.0834	Dam-03	0.1202
20	Dam-99	0.402	Dam-100	0.2194	Dam-03	0.0834	Dam-52	0.1202
21	Dam-100	0.402	Dam-44	0.1535	Dam-52	0.0834	Dam-57	0.1202
22	Dam-80	0.3725	Dam-66	0.1514	Dam-57	0.0834	Dam-73	0.1202
23	Dam-44	0.2974	Dam-85	0.1513	Dam-73	0.0834	Dam-74	0.1202
24	Dam-66	0.2843	Dam-09	0.1513	Dam-74	0.0834	Dam-75	0.1202
25	Dam-85	0.2647	Dam-42	0.1513	Dam-75	0.0834	Dam-81	0.1202
26	Dam-38	0.2582	Dam-43	0.1513	Dam-81	0.0834	Dam-82	0.1202
27	Dam-37	0.2516	Dam-45	0.1513	Dam-82	0.0834	Dam-86	0.1202
28	Dam-39	0.2108	Dam-54	0.1513	Dam-86	0.0834	Dam-88	0.1202
29	Dam-41	0.2075	Dam-67	0.1513	Dam-88	0.0834	Dam-89	0.1202
30	Dam-40	0.2042	Dam-68	0.1513	Dam-89	0.0834	Dam-90	0.1202
31	Dam-90	0.1176	Dam-71	0.1513	Dam-90	0.0834	Dam-91	0.1202
32	Dam-42	0.1176	Dam-72	0.1513	Dam-91	0.0834	Dam-95	0.1202
33	Dam-43	0.1176	Dam-83	0.1513	Dam-95	0.0834	Dam-96	0.1202
34	Dam-45	0.1176	Dam-84	0.1513	Dam-96	0.0834	Dam-97	0.1202
35	Dam-54	0.1176	Dam-80	0.1486	Dam-97	0.0834	Dam-98	0.1202
36	Dam-67	0.1176	Dam-39	0.116	Dam-98	0.0834	Dam-99	0.1202
37	Dam-68	0.1176	Dam-26	0.1152	Dam-99	0.0834	Dam-100	0.1202
38	Dam-71	0.1176	Dam-25	0.0745	Dam-100	0.0834	Dam-11	0.0969
39	Dam-72	0.1176	Dam-20	0.0434	Dam-38	0.071	Dam-46	0.0969
40	Dam-83	0.1176	Dam-23	0.0309	Dam-37	0.0671	Dam-56	0.0969

Table A2. Rank position comparison for the scenarios (top 20).

Action	Rnk. Sc.1	Rnk. Sc.2	Rnk. Sc.3	Rnk. Sc.4	MSE Sc.1–3	Avg. Sc.1–3
Dam-02	2	1	19	18	10.1	7
Dam-03	3	2	20	19	10.1	8
Dam-52	4	3	21	20	10.1	9
Dam-57	5	4	22	21	10.1	10
Dam-73	6	5	23	22	10.1	11
Dam-74	7	6	24	23	10.1	12
Dam-75	8	7	25	24	10.1	13
Dam-81	9	8	26	25	10.1	14
Dam-82	10	9	27	26	10.1	15
Dam-86	11	10	28	27	10.1	16
Dam-88	12	11	29	28	10.1	17
Dam-89	13	12	30	29	10.1	18
Dam-90	14	13	31	30	10.1	19
Dam-91	15	14	32	31	10.1	20
Dam-95	16	15	33	32	10.1	21
Dam-96	17	16	34	33	10.1	22
Dam-97	18	17	35	34	10.1	23
Dam-98	19	18	36	35	10.1	24
Dam-99	20	19	37	36	10.1	25
Dam-100	21	20	38	37	10.1	26

Table A3. Rank position comparison for the scenarios (last 20).

Action	Rnk. Sc.1	Rnk. Sc.2	Rnk. Sc.3	Rnk. Sc.4	MSE Sc.1–3	Avg. Sc.1–3
Dam-22	88	84	88	88	2.3	87
Dam-30	86	85	83	83	1.5	85
Dam-10	84	86	84	84	1.2	85
Dam-63	85	87	85	85	1.2	86
Dam-31	78	88	86	86	5.3	84
Dam-29	89	89	89	89	-	89
Dam-50	90	90	90	99	-	90
Dam-34	91	91	91	97	-	91
Dam-35	92	92	92	98	-	92
Dam-32	93	93	93	95	-	93
Dam-01	94	94	94	90	-	94
Dam-06	95	95	95	91	-	95
Dam-07	96	96	96	92	-	96
Dam-14	97	97	97	93	-	97
Dam-28	98	98	98	94	-	98
Dam-33	99	99	99	96	-	99
Dam-51	100	100	100	100	-	100
Dam-53	101	101	101	101	-	101
Dam-92	102	102	102	102	-	102
Dam-102	103	103	103	103	-	103

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