Tailings: re-processing or safe storage? A proposal of optimization by multi-objective criteria

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Abstract - The disposal of mining waste and tailings is a controversial and frequent object of discussion that becomes especially radical when an accident occurs. Most of the ancient disposals have high contents in sulfides and heavy metals and the storage was designed without taking into consideration the dynamic changes in the chemical composition, as well as the alteration of the structural equilibrium due to the progressive erosion. This is the case of the Cabeço do Pião pile, constituted by tailings from a former processing plant that belonged to the Panasqueira Mine Complex in Central Portugal. Tungsten has been exploited in the area since the end of the XIX century but this tailing and waste rock deposit begun to store materials since 1927 until 1995. The structure has an height around 90 meters. As a component of the European project ERA-MIN "REMinE: Improve Resource Efficiency and Minimize Environmental Footprint" it is intended to compare solutions of re-processing the tailings, with competitive grades in W, Cu and Zn, with other storage destinies. The analysis will take into account an integrated approach considering simultaneously economic, social and environmental features. The overall characterization will be submitted to a multi-objective criteria optimization.

Keywords: Mine waste, tailings, optimization algorithms, re-processing, and tungsten.

1. Introduction

In many abandoned mining sites in Europe and worldwide, the disposal of rock wastes and tailings have high environmental impacts that imply several potential risks. Especially tailings originated by metallic mining can be harmful to the environment as they contain high concentrations in sulfides, such as pyrite (FeS_2), arsenopyrite (FeAsS), chalcopyrite (CuFeS2), besides other minerals such as wolframite ($(Fe,Mn)WO_4$) and cassiterite (SnO_2). Sulfides when exposed to oxygen and water may be oxidized with a subsequent formation of low pH effluents, known as Acid Mine Drainage (AMD), that may contain in solution several toxic metals originated by leaching of the residual minerals (Kagambega *et al.*, 2014). AMD may also be generated in underground works, although the impact is generally lower that at the surface. (Johnson, 2005). In this last case, a long term impact will be generated contributing to a systematic cumulative contamination of the surrounding soil and groundwater by allowing releases of As and other heavy metals when it exists sulfide-bearing minerals (Lim *et al*, 2009).

Mitigating the environmental impacts generated by mining waste on soil and water quality requires an understanding of the mineralogy of the orebody and its global chemical composition, including trace elements.

The chemical composition of the drainage can vary considerably from site to site, as well in time for the same site. This environmental damage is frequently associated with geotechnical instabilities that can generate a rupture followed by failure of the embankment, thus producing an accident of great proportions, as the last one occurred in Brazil in 2015, in Mariana (Minas Gerais).

Many of the technologies for reducing AMD have been based in covering the tailings with several layers of impervious materials (such as clays and HDPE), thus avoiding the infiltration of rainfall and simultaneously reducing the diffusion of oxygen.

Many of these ancient tailings disposals may contain metals with substantial economic value in the modern mineral market. Sometimes the grades are exploitable by actual standards or the tailings may contain metals that were not of economic interest at the time when the mining operation occurred and are in demand nowadays. As a consequence, in certain cases, the re-mining of those tailings may be considered (Eit, 2017).

The European project ERA-MIN "REMinE: Improve Resource Efficiency and Minimize Environmental Footprint", involves institutions from three countries: Portugal, Romania and Sweden that have a long history of mining activity in the last century. One of its main objectives is to evaluate the re-processing of mining wastes in chosen tailings disposals, in each one of these countries. Comparing it with other solutions using several criteria (economic, environmental, and social). The mines sites that will be studied in the project are Cabeço do Pião in Portugal (W, Sn Cu), Sasca in Romania (Cu, Ag Au) and Yxsjöberg in Sweden (W, Cu and fluorite).

The re-processing of tailings is a high complex problem, involving many different variables expressed in different metrics. The development of a tool that evaluates several possible solutions, and different criteria, manipulating variables expressed in different scales is a challenging uncommon and complex problem.

Besides, it involves research in alternative ore processing as well as in the implementation of new optimization processes. The feasibility assessment should be envisaged as a multi-objective optimization problem. The typical optimization solutions for this problem may present some difficulties when compared to a singular objective problem. Therefore, the search for alternative approaches can be efficient in solving this type of problems. Models of Artificial Intelligence based on Genetic Algorithms (GA) have been used as a great choice in several complex engineering problems (Leite *et al*, 2006).

The objective of this paper is to present an overview about a conceptual model that is in development as a component of the REMinE project. The model consists in a multi-objective criteria optimization using genetic algorithms to decide or to reject the re-processing of tailings considering integrated economic, social and environmental assessments.

2. Materials and Methods

The local of study of this paper is the Cabeço do Pião Tailings Disposal located in the Panasqueira Complex Mine area in Central Portugal. The initial mining activity begun by the end of 19th century and covered an area of more than 2,000 ha. The Panasqueira deposit is a Sn–W hydrothermal mineralization associated with the Hercynian plutonism, had been exploited mainly wolframite, cassiterite and chalcopyrite (W, Sn Cu), the latter two as by-products with minor content (Ávila *et al*, 2008).

The tailings from one of the Tungsten processing plant (The "Rio" plant) have been disposed since 1927 for 90 years ahead in the open-air pile deposit located near to Zêrere River reaching an height of approximately 90 m with estimated volume for the tailings of 731 034 m^3 (Figure 1).

Figure 1. Cabeço do Pião Pile (Google Earth, 2017).

The material deposited has high concentrations in some heavy metals, namely in Cu (0,25%), Zn (0,68%), W (0,41%) and specially in As (7,4%) (Ávila *et al*, 2008). These authors and Candeias *et al*. (2013, 2014), Silva *et al*. (2013) and Gonçalves, A. (2014) have thoroughly studied the geochemistry and the mineralogy of the tailings as well as the acid mine drainage impact in this area and downstream of Zêrere River.

This waste deposit has a potential risk of collapse, with many visible instability zones that may degenerate because of the frequent adverse climate conditions in the Panasqueira region. The grain size of the materials disposed in the Cabeço do Pião Pile is variable however most of them are very fine grained allowing for high specific surfaces available for chemical reactions.

Tailings samples were collected according to a regular grid on top soil of the Cabeço do Pião Pile in two sampling campaigns. They included 33 top soil samples for the characterization of the superficial contamination resulting from reactions interference of the original tailings with the tailings effluents that will be compared with elder measurements at the same location. All coordinates samples were determined by GPS (Global Position System) and georeferenced with UTM (Universal Transverse Mercator) system.

a. *Chemical Analysis*

Tailings samples collected in the campaigns went through a simple preparation stage before they were analysed in conformity to the instrument requirements.

The heavy metals were analyzed by Energy Dispersive X-ray Fluorescence (XRF) method using an X-MET8000 instrument (Oxford Instrument). The equipment was used in Mining Mode that allows fast and accurate analysis with low limits of detection in order to determinate impurities and penalty elements.

The mean results of the chemical analysis were within the 95% confidence limits of the recommended values given for the certified materials. The Relative Standard Deviation (RSD) was between 0% and 5%. The elements As, Cd, W, Zn, Cu and Fe were assessed and showed in Table 1.

Table 1. Chemical Analysis of tailings from Cabeço do Pião Pile.

Mean (ppm)	As	Cd	W	Zn	Cu	Fe
n=33[(1)]	128166	109	1333	5709	3606	198196
n=17[(2)]	73649	1227	4068	6843	2494	125000

Notes: (1) REMinE team, 2017; (2) Ávila *et al*, 2008.

3. Problem Formulation

An alternative solution to these tailings, with various composition is to reprocess them by physical and hydrometallurgical techniques, because this material was previously floated and then its particle size distribution is fine and extensive. Before starting the tailings re-processing is important to know how the material will be exploited from the original site and be transported to a potential re-processing plant. One possibility is to consider an initial stage where the material would be submitted to reverse flotation to depress the minerals and float the arsenic, creating a new type of tailings – the neo-tailings. As next, the depressed material may be processed in a leaching stage and the produced solution be treated to recover some of the metals with considerable economic value. Figure 2 shows a flowsheet with the proposed re-processing plant.

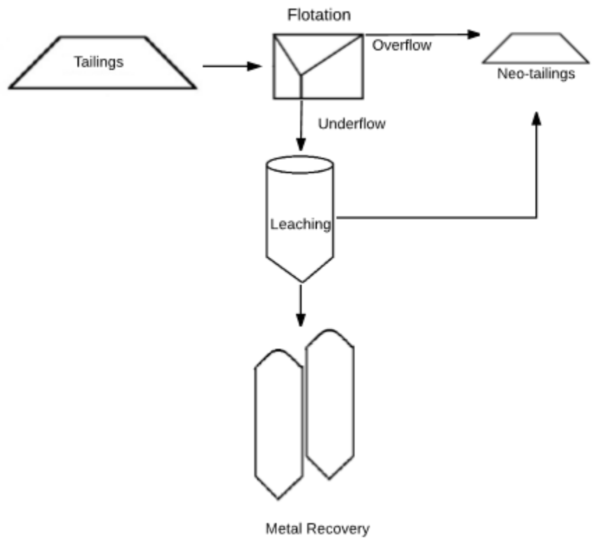

Figure 2. Simplified flowsheet proposed to the tailings re-processing.

The total design process involves numerous variables and objectives, which must be evaluated. The relative importance of each recoverable metal will depend on the quotation in the market (Huband *et al*, 2006). Therefore, the general formulation of tailings re-processing problem using a technologic and economic approach requires the global optimization of the unit operations involved in the processing flowsheet.

The re-processing plant also produce low environmental impacts being the most important the potential environmental impacts of the neo-tailings. The search for a sustainable and integrated management implies the reduction of the volume and the increase in the stability of the neo-tailings storage, thus minimizing the risks. Last one, it is assumed that the evaluation of the social factors are as important as the other aspects. The impacted population should be minimized, as well as the impacts generated.

It is impossible to satisfy all these objective functions without no detriment of any solution. Optimization problems with multi-objectives functions are solved by following a good solution, but not a single exact solution. This means, that the objectives generally are conflicting which prevents to find only one optimal solution. In general, if it is intended to optimize criteria simultaneously, the optimal solutions will be a volume of an equivalent solutions in an n-dimensional topological space. The meta-heuristic mathematical area that has been efficient in solving problems like this (Konak *et al*., 2006). The mathematical process of stochastic optimization consists in random searches of feasible solutions to hard problems or unknown solutions. In this case, Genetic Algorithm (GA) is the most useful method (Jones *et al*., 2001).

4. Genetic Algorithms

John H. Holland developed the basic Genetic Algorithms (GA) theory, in 1970, as a professor at the University of Michigan, in USA. He investigated mathematical analyses of adaptation and postulated the theory of evolutionary algorithms by a recombination of groups in a population by means of mating and mutation such as in biology (Holland, 1992).

Inspired by the Natural Selection, the algorithm must evolve a population composed of possible solutions to all problems involved, which are distributed randomly in a search space. Through a combined selection mechanism and the crossover and mutation operators the individuals are selected in this initial population and evolve at each offspring until an optimal solution is found according to decision-maker preferences (Costa & Simões, 2008).

The multi-objective solution to optimization problems by GA is generally done by matching each individual problem into a scalar fitness function. In this case, each single objective is evaluated and so it is attributed a weight according to its quality (Konak, *et al*, 2006). The expected solution will be around in the high-performance the multi-objective functions.

5. Proposed Genetic Algorithm

The first component to be defined is the solution representation because of the GA performance depends on a correct problem codification. The traditional language is a binary representation, particularly binary strings to represent an individual. In each individual or chromosome, a gene is a bit. The seeking for the best solution is looking at strings that have 1's or 0's (Holland, 1992).

To propose the GA design some questions must be discussed (Huband *et al*, 2006):

- What are the relevant parameters and variables for the re-processing plant?
- How evaluate each objective, how quantify these objectives or create a ranking of solutions?
- How could transform a function into chromosome able to breed and to mutate?

The understandability of the program logics and the ability to define the GA operators will be improved throughout iterations.

Figure 3 represents an overview from a proposal genetic algorithm by multi-objective criteria. Each operator and procedure are described below in conformity with the tailings re-processing plant.

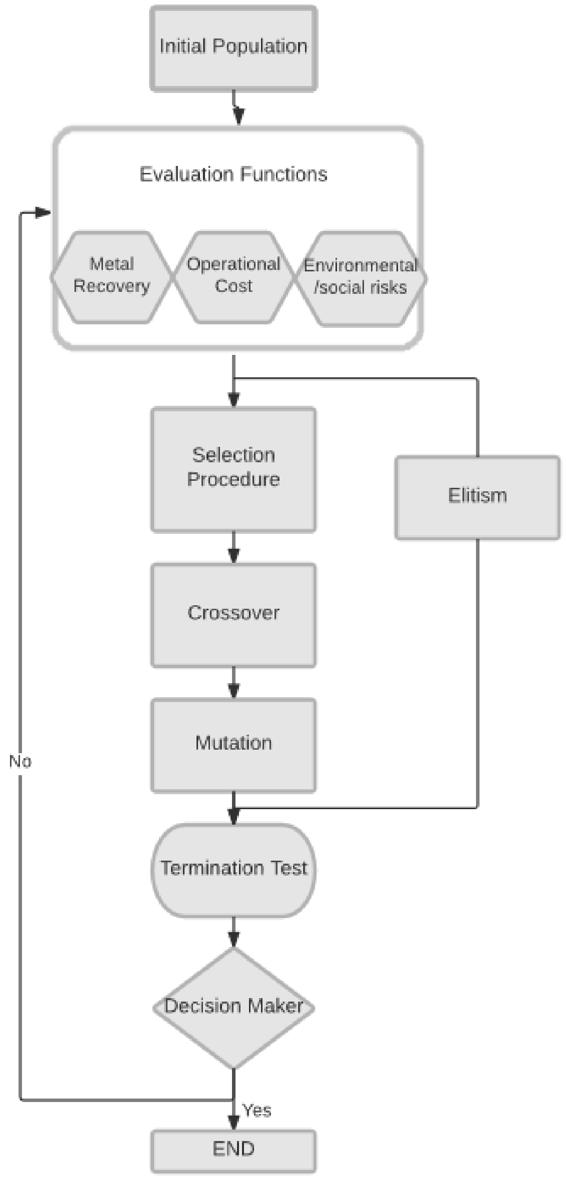

Figure 3. Outline of the multi-objective genetic algorithm proposal.

a. Design of initial population

To generate the initial population the size and the method of choice are relevant (Reeves, 2003). In this genetic algorithm, the initial population is compound by the circuit configurations, and will be characterized by scores such as the metal recovery, the new tailings quality and the social and economic features. Unfortunately, the population size will be framed by lower and upper limits that must guarantee that the optimal solution is included and the efficiency of algorithm is guaranteed.

b. Evaluation function

The evaluation function should provide a measurement of the quality of the solutions encoded by GA. In that case the evaluation functions are the objectives functions:

- Maximization of the metal recovery;
- Minimization of the operational cost;
- Minimization of the environmental and social risks.

c. Selection procedure

The selection procedure consists in a method that combines the crossover and mutation operators to selecting the survivals for the new generation. One frequent method is to evaluate the solutions by a weighted criterion. In this case, the selection procedure will transform multi-objective functions into a scalar fitness solution by a sum approach in which each function will be weighted (Murata *et al*, 1996).

d. Elitism

Some genetic algorithm elect an elitism function as a condition to select the best value. And this is regarded throughout the generations and will preserve an elite individuals in this multi-objective genetic algorithm (Costa & Simões, 2008). The bad individuals will be replaced, in that case may be the worse metal recovery expected, for example.

e. Crossover

During the mating process the crossover operator is used to recombination the genes of two individuals, with a predefined probability. To each crossover process a new single offspring is generated with the best parent's genes.

f. Mutation

The offspring generated from the mating process is subject to mutation phenomenon, as in natural selection. By a lower probability, the mutation operator is used to modify one or more genes in the offspring (Leite *et al*, 2006). This process will guarantee the GA is continuously diversified.

g. Termination Test

A stopping test should be previously determined to limit the programming time. For this GA, the terminator point is the number of individuals (feasible circuit configuration) in the initial population.

h. Decision maker

This multi-objective genetic algorithm at the end of the simulation will be in the vicinity of the high solution with all involved features respected.

6. Conclusions

This paper is an initial proposal of optimization by multi-objective criteria, to evaluate if the tailings re-processing is a feasible alternative. The methodology has potentiality to be further used as an innovative toll to evaluate other old tailings. Although the genetic algorithm routine is difficult to implement, this technique is used to solve major engineering problems.

The compiling of our genetic algorithm is in development, and the operations conditions will be inserted after all the characterization is done, interacting as feedback to the experimental planning. But, if the re-processing plant reveal unfeasible by technical restrictions, other solutions will be proposed for the tailings from Cabeço do Pião Pile.

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