Multi-criteria decision model for assessing arsenic abatement technology in Chilean mining

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***Abstract*—This study focuses on providing a framework to assist the technology evaluation to produce stable arsenic compounds in mining in Chile. Technological processes offer different attributes to show consideration for the environment, arsenic capacity reduction, process viability and efficiency. The objective is to determine the most appropriate technology for arsenic abatement that comes from the casting powders. Empirical data is collected for designing a multi-criteria decision model based on expert judgment allowing the identification of high-priority requirements to choose the appropriate technology to produce stable arsenic compounds. The study provides a basis for setting priorities and decision-making beyond the project evaluation indicators for incorporating technology that could help to reduce arsenic in any type of mine presenting this difficulty.**

***Index Terms*—MCDM, arsenic abatement technology, mining.**

I. Introduction

There is a great concern about the recent awareness related to the adverse effects of arsenic causing cancer in humans although it has been advised long ago by medical statistics. Minerals containing copper and arsenic and mineralogical associations between their compounds are particularly common in the Chilean deposits. Moreover the Sanitary Regulation on Hazardous Waste Management (Decree No. 148 of June 12, 2003, published in the Official Gazette on June 16, 2004), indicates great importance to design processes to bring them down and restricting them efficiently and safely. The context of the problem addressed in how to deal with those situations where the harmful effects of arsenic and its compounds on human health . In late 2001, the EPA (Environmental Protection Agency of the United States) lowered the maximum contaminant level allowed for drinking water from 50 μg/L As to 10 μg/L As. The reason for the reduction was that the National Academy of Sciences of the United States released its opinion about the above limit was not protecting the population risk of cancer [1] .

Despite the statistical relationship, known for a long time, between arsenic and cancer, only until recently we have more information about how this inorganic element causes the disease. Arsenic has a high affinity for proteins, lipids and other cell components and cause virtually suicide of cells to fuse the ends of chromosomes as described byin W. Chou et al. [2].

Currently, the most dramatic global effects are those that happened in Bangladesh, where hundreds of thousands of people suffering from acute and chronic diseases (poisoning and skin diseases) (cancer, diabetes and cardiovascular disease) caused by the consumption of water from wells contaminated with arsenic.

Chile is also affected by this problem, mainly at north of our country, Region II. However, Chile has had considerably advances lately, to the extent of domiciliary potable water networks and the installation of appropriate purification plants. Thus, while in the period 1958 - 1970 the average level of arsenic in drinking water of cities in northern Chile was 860 μg/L, currently is only 40 μg/L As average.

The origin arsenic in water may be geological (geological features of rocks and soils that cross watercourses) or due to human activities: agriculture and/or mining.

The interest of this study is also in considering the economic aspect which involves the potential cost savings depending on the technology chosen and the impact on environmental protection, especially of a vital element in our life as it is water. Today global efforts are focused on how to endure this resource for future generations, where the care of water plays a fundamental role which should be taken into account.

Regarding the work that has been done before, we can mention the work of Ferreccio et al. [3] , which shows as Chile is concerned, mainly in Region II , where some people are suffering from acute and chronic diseases caused by water from wells contaminated by arsenic; Torres [4] developed a methodology based on the integration of Geomatic and techniques of Multicriteria Evaluation, allows obtaining a model of priorities for the environmental restoration of abandoned mine sites and heavily polluted by arsenic, Jenkins et al. [5] used the Analityc Hierarchy Process (AHP) to evaluate the environmental and social implications in mining and Zulueta et al. [6] shows the multi-criteria analysis as a successful prospect for the sustainability assessment of mining projects.

Prior work has been done by the authors related to the technology selacction applying AHP. [11], [12].

In order to contribute dealing with this problematic it is of interest to count upon a method to find out the most advantageous technology to produce stable arsenic compounds technology. The purpose is to presents a framework to help the evaluation of technology in Chilean mining. Technological processes offer different attributes, in relation to the environment, arsenic abatement capacity, viability and efficiency of the process. The objective is to determine the most appropriate technology for arsenic abatement comes from the casting powders. AHP is used to develop a new multi-criteria decision model based on expert judgment for identifying high-priority requirements for choosing the most advantageous to produce stable arsenic compounds technology. In Section II the most relevant processes for the treatment of arsenic is presented, Section III shows how the AHP model is used to establish the decision criteria. The main results are provided in section IV including a benefit-cost estimation .Conlusions are presented in section V.

II. System Description

In many places the removal of arsenic from mine tailings, smelter dust or other industrial applications is subject to strict regulation. That said, the market offers innovative solutions for the management of arsenic that ensure regulatory compliance and improve social and environmental footprint. In many cases the arsenic can be processed to obtain a marketable product. The processes are designed to remove, discard, recycle, detoxify or "fix" arsenic compounds, usually by pressure oxidation. The best known processes [13], [14], [15], [16] are as follows:

Process 1: Precipitation hydrated arsenic as ferric arsenate to recover copper.

The casting powders are leached with acid to generate a rich solution. This solution is sent to a chilling process arsenic. Subsequently the copper-rich solution is treated with hydrogen peroxide followed by treatment with ferric sulfate and limestone. Then reactors, the arsenic enriched fraction is separated, which is precipitated as hydrated ferric arsenic, a stable form of arsenic.

Process 2: Precipitation of arsenic as ferric arsenate to recover copper.

The hydrometallurgical process uses the average chloride to leach chalcopyrite concentrate and produce copper powder. Copper powder is converted into bars and other forms by continuous casting process. The concentrates were leached with a solution of sodium chloride and oxidation by Cu2 + ion to the temperature of 85-95 °C. This temperature allows obtaining stable arsenic residues.

Process 3: Autoclave leaching and precipitation of arsenic to recover copper.

This process begins with a slight regrinding the concentrate prior to being fed to the autoclave for the pressure oxidation at high temperature. The leached pulp is filtered and the solution is sent to solvent extraction and electrowinning. If the precious metal content warrants the solid is sent to a recovery circuit. Currently you can treat copper concentrate containing arsenic and recover copper and precious metals. Pressure leaching is a hydrothermal process can directly produce stable arsenic residues.

III. The multicriteria approach

The multicriteria approach considered two main stages: the first stage is devoted to identify significant criteria that may impact the choice of the technology for treating arsenic contained in smelting dust. The second stage corresponds to building a hierarchical structure incorporating critical categories at each level and their relationships. Once the basic structure is designed, the effort is focused on an evaluation process carried out with the team of experts comprising managers, process engineers and members of the senior management, being eight people who evaluated the technologies.

A. The main Criteria

The main criteria to be considered to meet the goal are:

Environmentally responsible (sustainable) refers to how the company is perceived. It is a generally accepted image of what a company “means” to its customers and owners/shareholders.

Reliability expresses a degree of assurance that the system works successfully for a certain period.

Efficiency refers to the resources and infrastructure available to treat water at the lowest possible cost, as measured by the unit cost of arsenic killed.

Availability of the system is a measure expressed as a percentage indicating the time that an operating system works with respect to the total duration desirable for the different processes.

Capacity refers to the quantity of water treated in the plants during a certain period of time.

Functionality refers to factors combination as infrastructure, equipment, materials, services, human resources, technology (type of treatment), operation hours, communications and transportation that make operational the capacity and efficient in handling plants any time of the day during the 24 hrs.

B. The hierarchy structure

The purpose is to structure a hierarchy model to determine which technology is best assessed in terms of criteria highly valued by influential people in the mining sector. Accordingly, a basic model of two-level hierarchy is designed . The levels and its nodes stand for the decision factors that contribute to achieving the goal. The decision factors are based on benchmarking with mining projects that purpose to generate greater productivity and make operations more sustainable. Fig. 1 shows the initial hierarchy described earlier, being a faithful representation of the analysis undertaken.

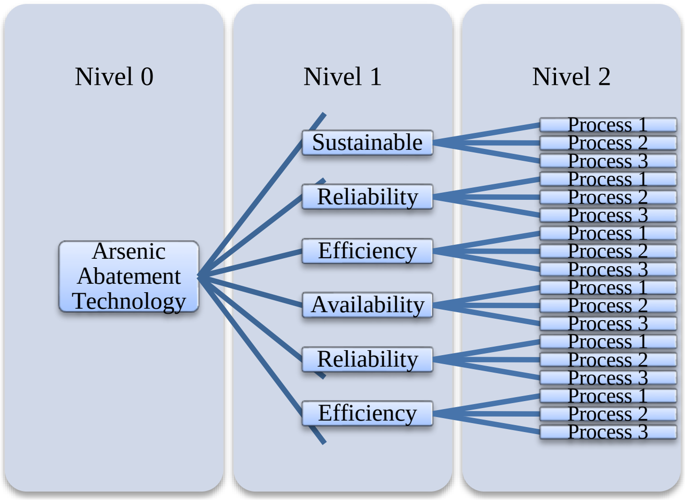

Fig. 1. The Arsenic Abatement Technology Hierarchy Model

The levels of the hierarchical structure are as follows:

Level 0: Indicates the goal, the main aim is to select the technology that best fit the requirements, named as: 'Arsenic Abatement Technology'.

Level 1: Includes alternative criteria that help determine which process is more likely to abate arsenic in mining.

Level 2: Includes all the candidate processes to abate arsenic in mining.

IV. Priority Results

A. *AHP model results*

Applying AHP methodology [7,8] and with the support of Expert Choice software [9], a relative ranking is obtained. The priority outcomes revealed that the environmental responsibility is a determining factor for deciding that technology is chosen for arsenic abatement comes from the casting powders.

Fig. 2 depicts the relative importance for the criteria considered. From these results, we can recognise that the main importance lies in the environmentally responsible and in the plant reliability.

This is consistent with the organization concern about building relationships of trust with their environment and create environmentally sustainable solutions for the treatment of various waste generated in the mining industry, pointing to the recovery of metals to improve the economic viability of the activity.

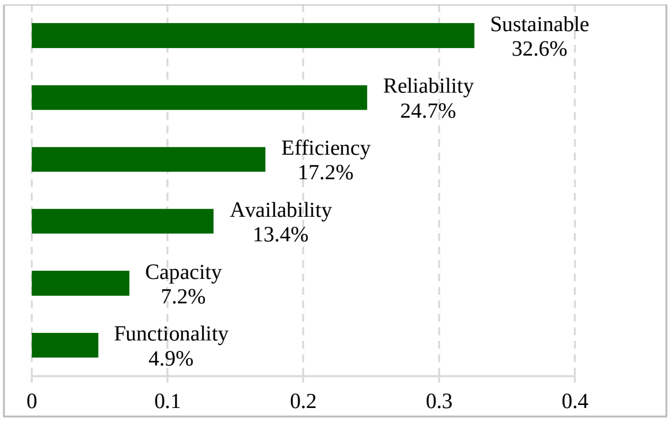

Fig. 2. Relative criteria priority

In a scenario in which the average grades are declining, the production of a tonne of metal will involve not only higher unit consumption of scarce resources such as water and energy, but also generate as much waste. While some have potential commercial value, not being treated and / or recovered may pose a risk to human health or the environment. Hence the importance of developing new technologies and aware as a society, seeking to generate complex waste that meet environmental standards at the lowest possible cost.

In this regard, the most feasible process is one that manages to be more environmentally responsible, have a high reliability and is highly efficient, which allows it to be viable from an economic point of view.

The first column of Table 1 indicates the global results for the global criteria for the three processes. For this particular case, 'sustainable' obtained the highest priority (32.6%) followed by 'reliability' (24.7%) and 'efficiency' (17.2%).

The results obtained through AHP for technologies are validated by the expert group. The priority judgments assignment showed low inconsistency.

TABLE 1 RELATIVE IMPORTANCE FOR PROCESS AND CRITERIA

	Global Criteria	**Process 1**	**Process 2**	**Process 3**
Criteria / Technology	***(%)***	***(%)***	***(%)***	***(%)***
Sustainable	0,33	0,42	0,22	0,36
Reliability	0,25	0,38	0,21	0,41
Efficiency	0,17	0,39	0,27	0,34
Availability	0,13	0,34	0,36	0,30
Capacity	0,07	0,37	0,28	0,35
Functionality	0,05	0,41	0,39	0,20
	Qualification	0,39	0,26	0,35

The technology recommended is the Process 1 grading with 39.0% (Sustainable 42.0%, Reliability 38.0%, Efficiency 39.0%, Availability 34.0%, Capacity 37.0%, Functionability 41.0%) followed by the Process 3 with 35.0% (Sustainable 36.0%, Reliability 41.0%, Efficiency 34.0%, Availability 30.0%, Capacity 35.0%, Functionability 20.0%) and finally the Process 2 with 26.0% (Sustainable 22.0%, Reliability 21.0%, Efficiency 27.0%, Availability 36.0%, Capacity 28.0%, Functionability 39.0%).

From this, it is interesting to think about the different weights assigned according to the criteria of relevance about the relevance is allocated to compliance with environmental regulations depending on the country where these projects are developed. This result could be used by decision makers for the distribution of resources and investment to develop technologies to reduce the environmental impact of mining waste and the proposal to partner with several mining companies operating in a specific area generating a cluster hazardous waste deposit.

B. Estimation of plant benefits and costs

To have an investment appreciation of the alternative treatment plants, an estimation of benefit cost (B/C) analysis is made. The ratio B/C is defined [10] as the ratio of the equivalent value of the benefits to the equivalent value of the costs (equation (1))

$$\frac{B}{C} = \frac{PV\ (benefits\ of\ the\ proposed\ project)}{PV\ (totall\ cost\ of\ the\ proposed\ project)}$$

$$= \frac{PV\ (B)}{1 + PV\ (O\&M)} \qquad (1)$$

For choosing the most appropriate technology to abate arsenic, Table 2 summarises the variables of 'investment', 'cost of annual operation and maintenance' and 'annual benefit' to be considered:

TABLE 2 COST AND BENEFIT VARIABLES

Investment	Annual operation and maintenance cost	Annual benefit
• Mining equipment	• Energy	• Decreased inefficiency losses
• Processing plant	• Chemical inputs	• Autonomy
• Ore transport routes	• Maintenance	• Environmental benefit
• Power lines	• Materials	• Quality assurance
• Personal	• Wages	• Increased treatment capacity

Through fig. 3,4 and 5 is posible to visualize the project evaluation for each process.

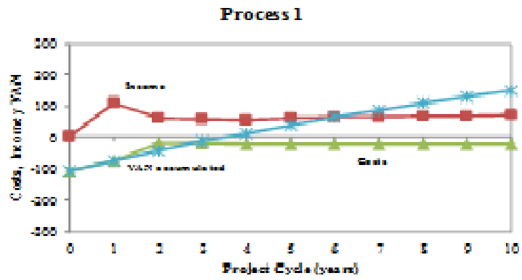

Fig. 3. Project evaluation for process 1

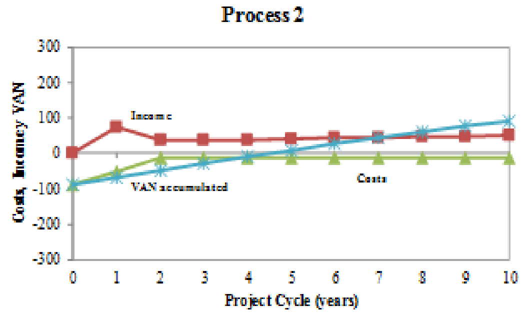

Fig. 4. Project evaluation for process 2

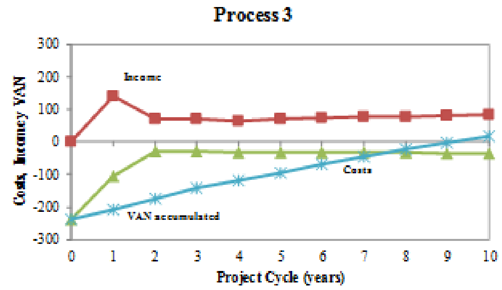

Fig. 5. Project evaluation for process 3

Given that a project is acceptable if the ratio B/C is greater than or equal to 1.0. Table 3 indicates that the three processes outlined in this paper are feasible being evaluated with a horizon for ten years.

However, the best result at the discretion of ratio B/C is more convenient process 1, followed by Process 2 and Process 3 finally.

TABLE 3 PROJECT EVALUATION INDICATORS

Indicators	Process 1	Process 2	Process 3
Discount rate	9,0%	9,0%	9,0%
Internal rate of return	33,6%	27,1%	10,6%
Ratio B/C	2,4	2,0	1,1
Payback	4,0	5,0	10,0

To support the decision on which process you should use to abate arsenic from the smelter dust, we considered B/C as another important factor to not ignore the economic aspect, since it is very important when making a decision about which process to choose for mining companies. Fig. 6 shows the total relative weighting (blue) and benefit cost ratio (red) for the three processes, in terms of the dynamic sensitivity.

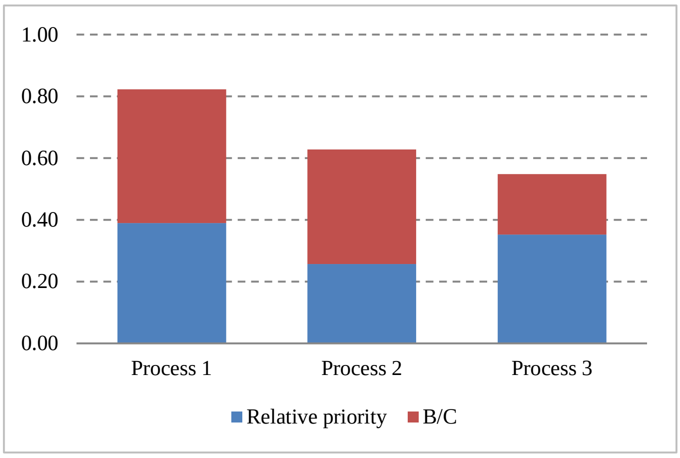

Fig. 6 relative weighting (blue) and benefit cost ratio (red) for the three processes, in terms of the dynamic sensitivity.

In this case, we can see that process 1 is superior to all other processes in both relative priority and the ratio B/C, however Process 2 despite having a lower relative priority over the Process 3, it has a greater ratio B/C, which results in weighing both criteria Process 2 is the best option Process 3.

V. Conclusions

In this study, we have presented a real-world situation for the technology to make more feasible the mining operation under the context of the growing demand for generating business growth in a sustainable manner through the AHP. The methodology has proven to be a useful tool for structuring and managing this decision problem, which allows the recognition of the issues that directly affect the selection of arsenic abatement processes.

Given the existence of different aspects and decision variables to select the most appropriate technology to enable decouple economic growth from environmental degradation, development of a decision model using AHP was advantageous because it provides a deeper understanding of the priority needs for choice of the technology.

Supporting the results delivered by the AHP method to estimate the benefit and cost analysis consolidates the study. Both approaches show that it is feasible process 1 through AHP.

Acknowledgment

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References

[1] Goyer R., (2001). “Arsenic in Drinking Water: 2001 Update”, National Academy of Sciences, Board on Environmental Studies and Toxicology (BEST).

[2] Chou W., Hawkins A., Barrett J., Griffin C., and Dang C., (2001). “Arsenic inhibition of telomerase transcription leads to genetic instability”, Journal of Clinical Investigations, vol 108, pp. 1541–1547.

[3] Ferreccio C. González C., Milasavjlevic V., Marshall G., Sancha A.A. and Smith A., (2000). “Lung Cancer and Arsenic Concentrations in Drinking Water in Chile”, Epidemiology 11(6), pp. 673–679.

[4] Torres, J. (2015) Establecimiento de prioridades para la recuperación ambiental de sitios de faenas mineras abandonadas en la región de Atacama. Sustainability, Agri, Food and Environmental Research 3(3): p. 8-19.

[5] Jenkins, H. & Yakovleva, N. (2006). “Corporate social responsibility in the mining industry: Exploring trends in social and environmental disclosure”. Journal of Cleaner Production 14(3-4): pp. 271–284.

[6] Zulueta, A., Asencio, J., Leyva, D., Montero, J. (2013). Sustentabilidad empresarial de proyectos mineros: el análisis multicriterio como perspectiva acertada para su evaluación. Minería y Geología, Vol. 29, No. 4, p. 79-94.

[7] Saaty, T.L. (1997) Toma de Decisiones Para Líderes. El Proceso Jerárquico Analítico. La Toma de Decisiones en un Mundo Complejo, RWS Publications, USA.

[8] Saaty, T.L. (1998) Método Analítico Jerárquico [AHP]: Principios Básicos. En Evaluación y Decisión Multicriterio, Reflexiones y Experiencias, Editorial Universidad de Santiago, Santiago.

[9] Saaty, T.L. (1983) Expert Choice, Extracted from link http://expertchoice.com/ (December 10th 2012).

[10] Sullivan, W., Wicks, E. and Luxhoj, J. (2004) Ingeniería Económica de DeGarmo, Pearson, México.

[11] Pérez, A., Oddershede, A. and Mena, M. (2010) ‘Wastewater treatment system selection using the analytical hierarchy process’, The Operations Research Society Annual Conference OR52, Egham, London, UK.

[12] Macuada, C., Alarcón, R., & Oddershede, A. (2015). Multi-criteria assessment to automate water treatment plants using the Analytical Hierarchy Process. J. Global Business Advancement, Vol. 8, No. 2, pp. 236–246.

[13] Escobar V. and Monhemius J., (1988). “The Mineralogy of Arsenates Relating to Arsenic Impurity Control”, Arsenic Metallurgy Fundamentals and Applications, Reddy el al. Editors, The Minerals, Metals and Materials Society, Warrendale, P.A., U.S.A., pp. 405–453.

[14] Monhemius J. and Swash P., (1999). “Removing and Stabilizing As from Cooper Refining Circuits by Hydrothermal Processing”, Journal of Metals, vol. 51(9), pp. 30–33.

[15] Riveros P., Dutrizac J. and Spencer P., (2001). “Arsenic Disposal Practices in the Metallurgical Industry”, Canadian Metallurgical Quarterly, vol. 40, Nº4, pp. 395–420.

[16] Robins R. (2001). “Some Chemical Aspects Relating to arsenic Remedial Technologies”, U.S. EPA Workshop on Managing Arsenic Risks to the Environment: Characterization of Waste, Chemistry, and Treatment and Disposal.