GeoAmericas2020
4th PAN AMERICAN CONFERENCE ON GEOSYNTHETICS
26-29 APRIL 2020 • RIO DE JANEIRO • BRAZIL

Technical / Economic Assessment of Geosynthetics Selection for a Tailings Impoundment Impermeable Liner in the Peruvian Andes

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ABSTRACT
Commonly, tailings impoundment does not have an impermeable liner system, then if seepage flow contains acid water or precipitated metals from tailings, this can cause consequences or serious impacts in the ecosystem. The magnitude of the impact depends on the acidity generation degree or metal concentration that the tailings may have and the amount of seepage flow. In those cases, a geomembrane liner system is needed.

This research is developed based on a project where the geosynthetics selection is important because the large area of the tailings impoundment to be lined and also because the chosen geosynthetics has to meet technical restrictions of the project, such as differential settlements.

Nowadays, there are a variety of geomembrane to be used as liner system for tailings impoundment, for example HDPE, LLDPE, PVC and FPP. When the project needs to choose one geomembrane it must be done in order of geosynthetic assessment (cost and technical aspects).

The objective of this research is to evaluate and select the best geomembrane liner which reaches the requirements of a tailings impoundment located in the Peruvian Andes through the Choosing by advantages method (CBA method). This methodology consists on the possibility to separate the estimate cost from valuable attributes of each alternative. In the technical aspect, the geomembrane will be evaluated by their performance of differential settlements, and in the economic aspect by costs of supply and installation will be considered.

KEYWORDS

Multicriteria decision-making, Choosing by Advantages, CBA, Tailings Impoundment, geosynthetic liner, Andes

1. INTRODUCTION

Many times, there is a lack of relationship between rigorous analysis and a complete understanding of technical problems which could affect achieving real project benefits (Fischer & Adams 2011). When a specific project choice is necessary to be made, it must be supported on teamwork project evaluation, after an assessment according to project technical information, specialist' constructive experiences, recommended construction practices, environmental repercussions, economic and social aspects, construction schedule or stakeholder's contributions. The evaluation allows to reach a clear understanding of advantages in comparison with other alternatives that might be evaluated. Finally, the decision making in engineering's projects must be carried out with a reliable methodology of alternatives' selection.

In practice, many professionals use expert judgement analysis or multiple decision criteria analysis (MCDM) to evaluate the alternatives in projects. This methodology considers sustainable alternatives' selection based on cost such as Choosing by Advantages (CBA), Weighting Rating Calculating (WRC), Advantages for Bidder Selection (AHP), and others. Nevertheless, the actual literature does not provide many information or support criteria for MCDM method. This fact causes a lack of knowledge of MCDM method by project specialists (Arroyo 2004). This paper will analysis the CBA method, a modern methodology of alternatives' selection presented in the technical article "Comparison of Weighting-Rating-Calculating, Best Value, and Choosing by Advantages for Bidder Selection" (Annett Schöttle & Paz Arroyo 2017), which could provide practices advices for mining industry, focusing in the geomembrane's selection for the lining of tailings impoundment in Peruvian Andes.

2. GEOSYNTHETIC LINER

The impermeable liner with geosynthetics in tailing dams is becoming a worldwide trend, and it is more accepted and preferred by regulatory organizations, as long as there is an alternative and acceptable plan to mitigate risks (McLeod 2015). The liner has the objective to impermeabilize the tailing impoundment to warrant the contaminated water non-infiltration, therefore, the liner prevents natural ground and water table contamination; for this way minimize the risks of negative environmental impacts. Likewise, in the mining industry, a soil liner with low permeability is considerate like a second containment barrier that permit to get a smooth surface for geomembrane's installation.

The liner in the analyzed tailing dams in this paper, is made up for a geomembrane that rest on the ground. Particularly in this paper, the site area has a stratum clayey that works as a second containment barrier against any leakage through the geomembrane. In this sense, is important adequate selection and installation of liner, taking into account technical and constructive criteria being operationally functional and viable.

Others important aspects to considerate in the correct choosing of liner in the impoundment's tailings are the high levels of stress-strain, exposition of acids and basics process, adverse environmental conditions like ultraviolet radiation and extreme temperatures, and others. Under this hard condition, the ability of the geomembrane liner to remain flexible and provide containment of tailing may be affected. Currently in the market, a wide variety of geomembranes are available, differentiating by polymeric structure, molecular weight, crystallinity, copolymers and finally costs. Nevertheless, among the most used and those evaluated in this paper, the following are mentioned:

2.1 *HDPE (High Density Polyethylene)*

HDPE was created in Germany in the beginnings of the 70's, defined like a polymeric flat at least one and half millimeters thick. The HDPE geomembrane is normally black because of the Carbon Black Content added to protect them for UV radiation. The Carbon Black Content is between 2% and 3% (Müller 2007).

2.2 *LLDPE (Lineal Low Density Polyethylene)*

This geomembrane has similar characteristics like HDPE, but the difference is the percentage of mass of α-olefins (butene-1, hexene-1, octene-1). The α-olefins form lateral branches in the long ethylene chain, which increases the anchor strength. For that, HDPE materials have a higher resistance to stress cracking than LLDPE geomembranes. The Carbon Black Content is between 2% and 3% (Müller 2007).

2.3 *FPP (flexible polypropylene)*

This geomembrane present thermal stability, allowing easy installation because the expansion and contraction is less than HDPE and LLDPE, generating fewer wrinkles. It can contain liquids with temperatures higher than 100 ° C, high resistance to stress cracking, which can be 4 or 5 times more resistant to the HDPE or LLPDE geomembrane and with multiaxial elongation of approximately 120%, exceeding the HDPE and LLPDE

2.4 *PVC (Polyvinyl Chloride)*

It is one of the most common thermoplastic materials due to its low cost, durability and versatility for various applications, consisting of the polymerization product of the monomer units of vinyl chloride. They have good chemical resistance, good stability in contact with many chemical agents and limited stability against heat.

2.5 *EPDM (Ethylene Propylene Diene Monomer)*

One of its most important properties is the resistance to aging, heat and ozone, because carbon black can be found even in quantities greater than 40%. These properties arise as a result of their chemical composition, without plasticizers, which is why it is considered a rather inert material and its chemical composition is very stable over time. This type of liner can reach elongation values at break of 500% (Sheirs 2009).

The Table 1 presents the advantages and disadvantages that show geomembranes mentioned previously.

Table 1. Advantages and disadvantages of commonly used synthetic geomembranes (modified from Scheirs 2009)

Geomembrane	Advantages	Disadvantages
HDPE	Broad chemical resistance Good weld strength Good low temperature properties Relatively inexpensive	Potential for stress cracking High degree of thermal expansion Poor puncture resistance Poor multiaxial strain properties
LLDPE	Better flexibility than HDPE Better layflat than HDPE	Inferior UV resistance to HDPE Inferior chemical resistance to HDPE

Geomembrane	Advantages	Disadvantages
	Good multiaxial strain properties	
fPP	Can be factory fabricated and folded so fewer field fabricated seams Excellent multiaxial properties Good conformability Broad seaming temperature window	Limited resistance to hydrocarbons and chlorinated water
PVC	Good workability and layflat Behavior Easy to seam Can be folded so fewer field fabricated seams	Poor resistance to UV and ozone unless specially formulated Poor resistance to weathering Poor performance at high and low Temperatures
EPDM	Good resistance to UV and ozone	Low resistance to oils, hydrocarbons and solvents Poor seam quality

Some technical aspects to choose in a correct way some materials mentioned previously are puncture resistance, tear resistance, elongation capacity for settlement that could generate in the foundation and the exposition to project's weather conditions to long term.

In some cases, when the soil in the impoundment tailing are made up of compressible materials, as part of the design of the liner, differential settlements are take into account that would happen in the cycle life of tailing dams, which has to be estimated with analytic methods or numerical methods taking into account the applied loads. That permits the designer indicate the areas where could be settlement problems higher than allowed or significant differential settlement. In the cases of soft soils, it can be removed (depending of potential) or could treated applying dynamic consolidations, application of get grouting, gravel columns or modification of mining structure' geometry, to avoid the negative effect of settlements.

3. SITE CONDITIONS

3.1 Site description

The Project is developed in a site with high water potential in the central sector of Central Mountain of the Andes, so special considerations have been taken for the design for not impact natural resources of the site. The choose site for tailings storage is a wide ravine with a throat at the bottom, which allows the construction of tailing dam that serve like a containment of tailing. However, geotechnical characteristics in the impoundments and partially in the dam site evidence mostly the presence of clayey soils of lacustre origin.

As part of the project, a geological mapping was carried out with the support of geotechnical investigations (borehole and test pit) carried out in order to identify geological features and the geological-geotechnical units present. This units are presented in the Figure 1 and correspond to the following:

- Colluvial deposit: It is distributed in the south and west of the study area and is classified according to the Unified Soil Classification System (SUCS) as GP, GP-GM, GM and GC.
- Alluvial deposit: It is distributed in the east of contingency dams. It is classified according to SUCS as GP and GM.
- Lacustre deposit: It is distributed in the center of project site underlying the organic soil, inferring approximately in a potential of 25 meters. It is classified according to SUCS as SC, CL y ML.
- Morrenic deposit: It is distributed in the north and east of project site, inferring approximately in a potential of 37 meters. It is classified according to SUCS as GW, GP, GW-GC, GP-GM, GP-GC, GM, GC, SW, SP-SM, SC-SM, SC, CL, CL-ML, ML y CH.
- Residual soil: It is distributed in the northeast of project site, inferring approximately in a potential of 13 meters. It is classified according to SUCS as SC-SM and SM.
- Rock basement: Presence of limestone sedimentary rocks whose resistance are between medium and high (R3 and R4).

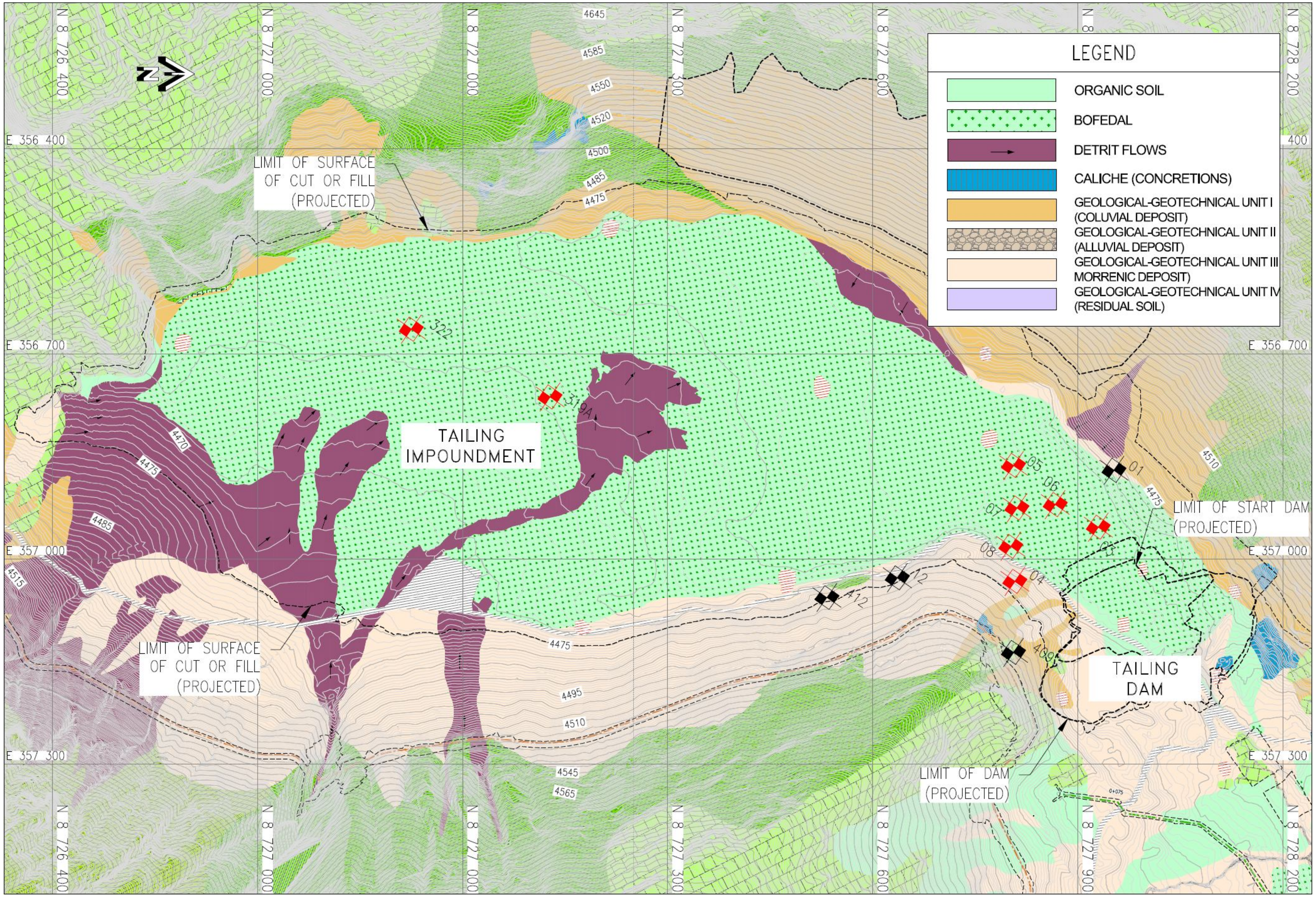

Figure 1. Geological-geotechnical units present in the project area.

3.2 Settlement analysis

The solution of the differential equation of the one-dimensional primary consolidation (Terzaghi & Frohlich 1936) was used, for the conditions where the increase in efforts within the soil is greater than the pre-consolidation pressure. Much of the area of impoundment tailing presents highly compressible clays that important settle by loads of tailings dispositions. The deformation parameters obtained of tests unidimensional consolidation are shown in Table 2.

Table 2 Deformation parameters

Material	Saturated specific weight ɣ (kN/m^3)	Void ratio (e_o)	Preconsolidation pressure (Pc)	Consolidation coefficient (Cv)	Compression index (C_c)	Recompression index (C_r)
lacustre deposit	17	1,58	35	1,57x10^{-9}	0,34	0,15

The operation of filling of tailing dams is estimated in 12,3 years, so the level of tailing will increase and as a consequence the stress in compressible soils will increase. The saturated density of tailing is considerate to 19,3 kN/m^3, obtained for decantation tests.

In accordance with mentioned previously, the following considerations area taking into account:

- The potential of lacustre soil founded in the impoundments is between 2 m and 25 m. This calculation of settlements was developed each meter. A correlation polynomial was used between the settlements and the depth of the clay, the settlement was estimated at any depth less than 25 m.
- Due to the nature of lacustre soils and according with values of properties of deformation and hydraulics, the primary consolidation was estimated taking several years; also, the secondary consolidation was result smaller than primary consolidation, so for that reason, it has not been considered.
- In the test pit's register and sections, it can be seen below the lacustre soils is the morrenic deposit. Due the morrenic deposit is a soil granular and the low compressible, it has been considerate a maximum settlement of 50 cm, for purpose to simplifying the calculations and being conservative.

The table 3 shows the results of settlements calculated at the location of test pit where thicknesses greater than 2 m of lacustre deposit, the clay found in the impoundment tailings presents a maximum settlement of 3,24 m for a stratum of 24,5 m. Also, in the test pit CA-AR14-01, CA-AR14-04, CA-AR14-08, CA-AR14-12, CA-AR18-412 y CA-AR18-404, were found the thickness of 2 m in the lacustre soil, underlay of that strata found rock basement, so for that reason, It is estimated that not happen settlement in a morrenic soil. In the vicinity of these two different deposits will generate differential settlement, a consideration that must be taken into account for the choice of geomembrane.

Table 3 Settlement results

Description	lacustre soil	Morrena	Total
CA-AR14-06	3,34	0,50	3,84
CA-AR14-07	3,34	0,50	3,84
CA-AR18-319A	3,34	0,50	3,84
CA-AR14-05	2,98	0,50	3,48
CA-AR14-03	2,89	0,50	3,39
CA-AR14-08	2,82	0,50	3,32
CA-AR18-322	2,77	0,50	3,27

Differential settlements cause multiaxial deformations in the geomembrane, which the HDPE geomembranes are not able to withstand (Smith & Orman 1994). A multiaxial test (ASTM -5617) could simulate the out-of-plane deformation, which occurs when differential settlements occur. Using a pressure recipient and with air constant flow, the sample of geomembrane deforms and gradually lengthens into a bubble. The maximum deflection point, the flow rate and the pressure are controlled until the eventual rupture of the sample. The result is considered to be representative of the filed behavior (Shiers, 2009).

Schiers (2009) recommends, for differentials settlements, geomembranes must have excellent elongation and flexibility, which are inherent properties of materials such as LLDPE or fPP.

4. INVESTIGATION METHODS

4.1 Multicriteria decision making

The multicriteria analysis is a support tool in the decision making during the planning process that allows integrate different criteria according with the opinions of stakeholders in a single analysis framework to give an integral vision. Decision making can define as the study to identify and choose alternatives based on values and preferences of the decision maker. This support tool can reduce the uncertainty about some alternatives to permit a reasonable choice between them, therefore allowing help people or teamwork to choose the best alternative using different criteria.

However, when the decision making has multiples criteria arise a lot of problems, like how define the weights of each criteria, which dependency has preferences than others, which conflicts exists among the criteria, and other aspects. These problems seem to complicate the decision and it is necessary to use sophisticated methods such as multicriteria decision-making methods, among them we have the CBA, WRC and AHP methods.

Many investigations focus in the implementation of method CBA in the design process like Grant & Jones (2008); Parrish & Tommelein (2009); Arroyo, *et al.* (2014); Kpamma *et al.* (2015); Arroyo *et al.* (2016); Schöttle *et al.* (2015).

Schöttle y Arroyo (2016) compared the method CBA with Weighting Rating Calculating (WRC) and the best value selection (BVS) through sensitivity analysis. The result demonstrated the benefits to apply CBA and how to avoid the problem of mix value of advantages with cost. Arroyo *et al.* (2014) demonstrated CBA is better than AHP and WRC, in terms of providing transparency, supporting consensus and allowing the continuous improvement. This paper will use the method CBA taking into account the advantages mentioned previously.

4.2 Choose by Advantages or CBA

CBA is a method that supports successful decision-making using comparisons of advantages between alternatives. Suhr (1999) developed this method while he was working in the US Forest Service. EEUU. Arroyo (2016) mentions that the CBA method is based on four principles: (1) decision makers must learn and skillfully use sound decision-making methods, (2) decisions must be based on the importance of the advantage, (3) decisions must be anchored to the relevant facts, and (4) different types of decisions require different methods of decision making

In CBA, the decisions are based only in advantages (Principle 2) (Instead of disadvantages), avoiding double considerations. When the advantages are found, interested parties should asses the importance of this advantages making comparisons among them. The weight should assign in based the importance of the advantages (Rather than general criteria, factors or other types of data). (Suhr, 1999).

The definition of *attribute* is used like a characteristic, quality or consequence of one alternative. The definition of *criteria* is used like a decision's rule or a guide. A *must criterion* represents conditions each alternative must satisfy. A *want criterion* represents preferences of one or multiple decision makers. The definition of *advantage* is a benefit, gain, improvement. Specifically, an advantage is a beneficial difference between the attributes of two alternatives (Suhr, 1999).

4.3 Procedure of CBA

In this section, the application of CBA method to the case study will be detailed step by step:

Step 1: Identify alternatives

Due to conditions 'projects are necessary to have geomembranes with large capacity of multiaxial elongation. Among them, it proceeded to analyze the fPP of 0,75 mm, PVC of 1 MM and EPDM of 1,14 mm. Also, the most commonly use mining industry such HDPE (1,5 mm) and LLDPE (1,5 mm) geomembranes were taking into account as additional alternatives. The thicknesses selected for each geomembrane correspond to those most suitable for the project due characteristic of each material.

Step 2: Defining factors

The factor will allow to differentiate the alternatives, so it is necessary to identify the needs of the project. It was considerate the properties of geomembrane such as multiaxial elongation (Due the deformation that will have in the project), carbon black content (Due to the exposure during the operation, these could be oxidized and cracked in time), tensile properties like tear resistance, tensile strength at break point, deformation at break point and resistance of geomembrane seams.

With respect constructive aspects, it was considerate the productivity (performance and number of man-hours of work), the quantity of material supplied (due to its relation to the amount of work to be executed for the same area to coated) and the amount of rolls (it will directly impact on the installation time by the amount of overlaps that will need to be made, in addition to the considerations regarding the packaging, transport and storage that will be taken for the installation of the geomembrane).

Step 3: Define must / want to have criteria for each factor

The *necessary criteria* were made based on the needs of the project, taking into account technics and constructive aspects. Also, it has *want criterion* as "more is better" in almost all of the factors, except for the quantity of material and rolls, where the *want criteria* are "less is better".

Step 4: Decide the advantage of each alternative

Once the factors have been raised, the criterion is selected to identify the advantages. The advantage is the difference between the value of the factor of an alternative minus the alternative that has the lowest value of the factor. Therefore, keeping in mind that for each factor there will always be at least one alternative that does not have an advantage since it is the one with the least attribute with respect to that criterion. The most important advantage for each factor is shown in bold and underlined in Table 5.

Step 5: Decide the importance of each advantage

Among the most important aspects for the geomembrane to be selected for this project, it is mentioned: withstand differential settlements, appropriate resistance to UV exposure and that the installation process has a high performance with the least number of workers. In the Table 4 shows the order the factors to be evaluated were presented and the scale of importance assigned to each factor (weight that each factor will have). Additionally, it is important to highlight that one of the needs of the project is to have a geomembrane that has a greater multiaxial elongation; therefore, the multiaxial elongation factor is the one with the most assigned weight.

Table 4 Cardinal order of advantages

Cardinal order	Idv (Weight of the advantages)
Multiaxial elongation	100
Elongation at break point (%)	90
Carbon black content	80
Productivity (m^2/hh)	70
Amount of material supplied (m^2)	60
Tensile strength at break point (N/mm)	50
Tear resistance (N)	40
Extrusion Fillet Seams- Shear strength (N/25 mm)	25
Extrusion Fillet Seams- Peel strength (N/25 mm)	10
Number of rolls	5

Setp 6: Calculate the total importance of the advantages of each alternative

Once the *requirement criteria* and the weight of the advantages have been established, the values presented in Table 5 are those minimum values required for each geomembrane analyzed for the project and that are established by the Geosynthetic Research Institute (GRI) and by the Institute of PVC Geomembranes (PGI). Then the Idv of each factor was calculated in direct proportionality to the highest value (highlighted in bold and underlined) and to the weight of advantages. Finally, the sum of the advantages of the factors for each alternative is carried out

Step 7: Evaluate Cost Data

The cost if installation, supply and freight of the geomembrane was taken into account. The cost values for each alternative are shown in Table 5.

5. SIMULATION

After previous steps execution, the results show that the lowest cost alternative is LLDPE geomembrane with an amount that comes to $ 4 271 301,20. On the other hand, the higher cost alternative is EPDM geomembrane with an amount that comes to $ 12 254 270,41. This variation is due to the material cost of the EPDM geomembrane is very high, approximately $ 7,5/m^2, while the material cost of the LLDPE geomembrane is $ 2,84/m^2. In addition, the EPDM geomembrane installation is more expensive because requires more labor in placement and pieces welds for being more resistant.

Regarding the advantages, the Table 5 shows that the LLDPE geomembrane is the less advantage alternative, with a value of 180,45. On the other hand, the results show that the fPP geomembrane is the greatest advantage alternative, with a value of 318,28. This variation is due to the fPP geomembrane has greater multiaxial elongation.

Table 5 Analysis of geomembrane alternatives

Aspects	Factors	1,50 mm HDPE		1,50 mm LLDPE		0,75 mm fPP		1,00 mm PVC		1,14 mm EPDM	
		Adv.	IdV	Adv.	IdV	Adv.	IdV	Adv.	IdV	Adv.	IdV
Properties	Tensile strength at break point (N/mm)	40		16		11		17		***9,6***	
	Criterion: more is better	**30,4**	Adv.: 40,0	6,4	Adv.: 8,4	1,4	Adv.: 1,8	7,4	Adv.: 9,7		
	Elongation at break point (%)	700		***250***		700		430		500	
	Criterion: more is better	450	Adv.: 90,0			**450**	Adv.: 90,0	180	Adv.: 36,0	250	Adv.: 50,0
	Multiaxial elongation	***25***		30		120		100		100	
	Criterion: more is better			5	Adv.: 5,3	**95**	Adv.: 100,0	75	Adv.: 78,9	75	Adv.: 78,9
	Tear resistance (N)	187		150		45		***44***		53	
	Criterion: more is better	**143**	Adv.: 50,0	106	Adv.: 37,1	1	Adv.: 0,3			9	Adv.: 3,1
	Extrusion Fillet Seams-Shear strength (N/25 mm)	524,8		393,6		***109,3***		336,7		153	
	Criterion: more is better	**95**	Adv.: 10,0	65	Adv.: 6,8			52	Adv.: 5,5	10	Adv.: 1,1
	Extrusion Fillet Seams-Peel strength (N/25 mm)	341,1		288,6		87,5		65,6		***35***	
	Criterion: more is better	**70**	Adv.: 25,0	58	Adv.: 20,7	12	Adv.: 4,3	7	Adv.: 2,5		
	Carbon black content	***2,5***		***2,5***		8,5		***2,5***		35	
	Criterion: more is better					6	Adv.: 12,9			32,5	Adv.: 70,0
Construction aspects	Amount of material supplied (m²)	1 105 220		1 085 130		1 075 080		***1 115 270***		1 205 700	
	Criterion: less is better	10 050	Adv.: 6,7	30 140	Adv.: 20.0	40 190	Adv.: 26,7			90 430	Adv.: 60,0
	Productivity (m²/hh)	125		156,3		156,3		125		***41,7***	
	Criterion: more is better	83,3	Adv.: 58,2	114.6	Adv.: 80,0	**114,6**	Adv.: 80,0	83,3	Adv.: 58,2		
	Number of rolls	1020		1005		995		560		***1 340***	
	Criterion: less is better	320	Adv.: 2,1	335	Adv.: 2,1	345	Adv.: 2,2	780	Adv.: 5,0		
	Score	**281,9**		**180,45**		**318,28**		**195,84**		**263,15**	
	CAPEX (MUS$)	**4,709**		**4,271**		**4,521**		**5, 532**		**12,254**	

As can be seen in Figure 2, the fPP geomembrane is the alternative that has the highest score and greatest advantages and is the second alternative with the lowest cost. On the other hand, despite the LLDPE geomembrane is the lowest cost alternative, this alternative has a lower score and lower advantages, that is why LLDPE geomembrane is the least appropriate for the project.

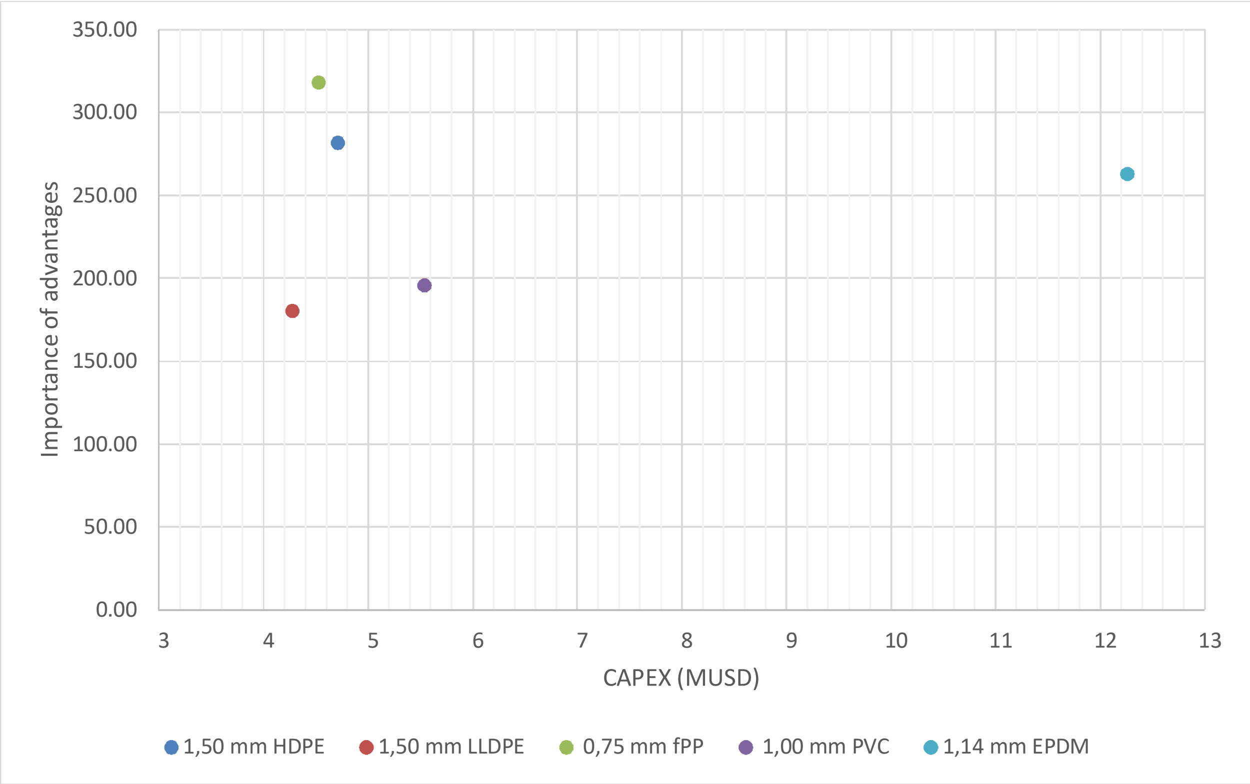

Figure 2 Geomembrane alternatives

6. CONCLUSIONS

In the mining industry, the problem arises in choosing the best impermeable liner system for tailings impoundment when they become a project necessity or a regulatory bodies requirement, which is not a simple choice, because it will depend on the technical characteristics, site conditions, weather conditions, construction processes, operational management, among others. The present investigation made a decision-making simulation using the CBA method that allows to select systematically the fPP geomembrane for project specific conditions due to the higher score obtained.

The present investigation allows to elaborate an advantages election system based on the project needs, as well as to identify the importance degree and to choose the best alternative that achieves the project requirements.

This document shows that the CBA method can be used in the mining industry for a technical choice of geomembrane lining on a tailings dam and impoundment and results a solid and fair method.

The CBA method also allows to identify that not necessarily the least expensive turns out to be the most advantageous. This is been reflected in the LLDPE geomembrane evaluation which has the lowest cost alternative, however, this alternative has lower score and therefore project lower advantages due to its lower elongation capacity reflected in low values of the multiaxial elongation properties, elongation at the breaking point, carbon black content, among others, in comparison with fPP geomembrane.

The CBA method also shows that fPP geomembrane alternative is the second one with the lowest cost, but it has the greatest advantages. Among its strengths are the following factors: multiaxial elongation, elongation at the point of breakage and productivity in geomembrane installation. These three factors are the most important because have the better weights assigned to them, therefore, the fPP geomembrane has the greatest importance of the advantages, reflected in its higher score.

In this research the authors have analyzed some geomembranes, which are the most used in mining projects. However, there are other options of geomembranes that have been of greater importance and could be considered in future researches such as bituminous geomembranes.

7. ACKNOWLEDGEMENTS

This research was supported by Anddes Asociados, which provided the necessary information for the multicriteria analysis. The opinions, findings, conclusions or recommendations expressed in this document are from the authors and do not necessarily reflect the views of the contributor.

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