



Leaching method selection for Caldag lateritic nickel ore by the analytic hierarchy process (AHP)



Sait Kursunoglu^{a,*}, Zela Tanlega Ichlas^b, Muammer Kaya^c

^a Abdullah Gul University, Department of Materials Science & Nanotechnology Engineering, 38100, Kayseri/Turkey

^b Department of Metallurgical Engineering, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jl. Ganesha 10, Bandung 40132, Indonesia

^c Eskisehir Osmangazi University, Department of Mining Engineering, Division of Mineral Processing, 26480 Eskisehir, Turkey

ARTICLE INFO

Keywords:

Leaching method
Caldag
Analytic hierarchy process
Sensitivity analysis
ExpertChoice® 2000

ABSTRACT

Leaching is an important process in hydrometallurgical operations. This process is used to extract metals from the ores by dissolving them in a lixiviant. It is desired that the leaching method is able to provide high extraction rate at minimal capital and operational costs. There are many parameters that can affect the leaching efficiency and thus, the process of selecting a leaching method is complex. In this study, the use of Analytic Hierarchy Process (AHP) method to select an appropriate leaching method for Caldag lateritic nickel ore has been performed. The application of AHP is assisted with the use of ExpertChoice® 2000 Software. The results shown that heap leaching (HL) is the most attractive leaching method with a rating of 0.592, followed by atmospheric leaching (AL), and high pressure acid leaching (HPAL) with ratings of 0.293 and 0.115, respectively. In addition, sensitivity analyses have been applied to investigate the impact of the main criteria on the alternative leaching methods. It was found that HPAL can be selected when economical main criteria decreased from 76.1% to 16.3%.

1. Introduction

There are three leaching methods currently applied for the hydro-metallurgical extraction of nickel and cobalt from lateritic nickel ores, namely high pressure acid leaching (HPAL), atmospheric acid leaching (AL) and heap leaching (HL). Each process has its own advantages and disadvantages. The main advantages of HPAL are that the process requires much lower acid consumption, higher nickel and cobalt recoveries and faster dissolution kinetics than the other two methods. The main advantages of AL are that it requires lower capital and energy costs than HPAL but able to provide comparable nickel and cobalt recoveries. Meanwhile, HL requires the least capital and energy costs among the three processes and produces clear leachate solution for downstream processing circumventing the need of a solid-liquid separation unit. This process, however, provides the least metals recoveries among the three, requires long leaching duration, inventory and cycle management (Kyle, 2010).

Selection of a leaching method for an ore is a function of many parameters and hence, a multi criteria decision making (MCDM) method can be used to aid the decision making process. This is done by evaluating a number of feasible alternatives using multiple choices of criteria and diverse criterion priorities to determine the most

attractive alternative over all criteria. Hwang and Yoon (1981) broadly classify the problems of MCDM into two categories: multiple attribute decision making (MADM) and multiple objective decision making (MODM). The former are preferred in the cases of selection problems while the latter are more appropriate in design problems. MODM methods have decision variable values that are designated in a continuous or integer domain with an infinite or very large number of choices, the best of which must satisfy the decision maker's constraints and preference priorities. On the other hand, MADM methods involve selecting from a finite number of alternatives.

Selection of the most appropriate leaching method is a multi-criterion and multi-objective decision bound by a set of constraints. In this paper, we use Analytic Hierarchy Process (AHP) to evaluate the three leaching alternatives. This method is a systematic approach developed by Saaty (1977) to make decisions based on experience, intuition and heuristics, and the structure is derived from sound mathematical principles. Owing to its simplicity and ease of use, the AHP has gained acceptance among decision makers. This process aids in structuring the complexity, measurement and synthesis of rankings. These features make it favourable for a wide variety of applications (Bhushan and Rai, 2004).

Recently, applications of decision-making techniques in mining

* Corresponding author.

E-mail address: sait.kursunoglu@agu.edu.tr (S. Kursunoglu).

operations have been performed by various researchers. For instance, the AHP method has been used to select mine equipment by Adebimpe et al. (2013) and Kursunoglu and Onder (2015), to select ore transport system by Owusu-Mensah and Musingwini (2010) and Zoran et al. (2011), to select underground mining method by Alpay and Yavuz (2009), and to select a location of the mine's mineral processing plant by Mohsen et al. (2010). The use of AHP for the selection of a leaching method, however, has not been reported in the literature. This study therefore studied the use of AHP for selecting the most attractive leaching method for Caldag laterite nickel ores based on the available technical and economical data from the application of HPAL, AL and HL to Caldag ore.

2. Application of leaching methods

2.1. Caldag heap leaching application

The first pilot-scale heap leaching application was performed by European Nickel in 2004. A close circuit system was chosen. The system was based on leach liquor metal concentration build-up in pond via recirculation of the pregnant leach solution (PLS) over freshly prepared ore. The process neutralized acid and eliminated any extracted nickel and cobalt lost prior to mixed hydroxide precipitation (MHP) process. The process aided the reduction of acid consumption and water usage, and the lowering of limestone consumption in the partial neutralisation unit. Acid concentration of the solution was adjusted to be 75 g/L. The particle size fraction of the ore was minus 25 mm. After 548 days of leaching tests, 79.4% Ni, 82.7% Co and 30% Fe were extracted from the ore. Acid consumption was determined to be 528 kg/t ores (Oxley et al., 2007).

2.2. Caldag high pressure acid leaching application

The high pressure acid leaching experiments were performed in an autoclave with 2 L capacity. 94.1% Ni, 94.0% Co and 1.7% Fe were extracted under the following conditions: leaching temperature of 250 °C, leaching duration of 1 h and particle size of less than 1 mm. Acid consumption was determined to be 325 kg/t ores. Notably, extraction of nickel beyond 95% is found to be difficult even when the harshest conditions were applied, i.e. at temperature as high as 260 °C (Onal and Topkaya, 2014).

2.3. Caldag atmospheric leaching application

Bench scale atmospheric leaching tests were carried out in a 250 mL Pyrex water-jacketed reactor equipped with a digital overhead mechanical stirrer. 91.9% Ni, 93.5% Co and 80.5% Fe were extracted under the following conditions: 2 M H₂SO₄, 90 °C, liquid-to-solid ratio of 10:1 (mL/g), stirring speed of 500 rpm, leaching duration of 6 h and laterite particles size of less than 0.053 mm. The results showed that there is no benefit gained in the leaching of nickel by grinding finer than 0.150 mm. Cobalt extraction increased with decreasing size fractions because of coarse and compact manganese oxides particles that associate with cobalt in the laterite ore (Kursunoglu and Kaya, 2016).

3. Analytic hierarchy process (AHP)

The AHP is one of multi-criteria decision making (MCDM) method that assists a decision-maker facing a complex problem with multiple conflicting and subjective criteria such as location or investment selection and projects ranking (Ishizaka and Labib, 2009). In short, it is a method to drive ratio scales from pair-wise comparisons. It is these scales that measure intangibles in relative terms. The comparisons are performed using a scale of absolute judgments that presents how much one element dominates another with respect to a given attribute (Saaty, 2008). The AHP seeks to break a problem down and then aggregate the

solutions of all the sub-problems into a conclusion. It facilitates decision making by organizing perceptions, feelings, judgments, and memories into a framework that displays the forces that affect a decision. In the simple and most common issue, the forces are adjusted from the more general and less controllable to the more specific and controllable (Saaty, 1999). In the first step of the AHP, a decision-making problem is divided into a hierarchical structure with decision elements such as objective, criteria, sub-criteria and alternatives. The division is carried out from the top to the bottom, from the objective to the criteria and sub-criteria to the final alternatives. A judgment matrix is shaped into according to a decision maker's judgment and used to compute the priorities of the elements. The comparison matrix is described as shown below:

$$A = \begin{bmatrix} 1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & 1 & \dots & w_2/w_n \\ \dots & \dots & \dots & \dots \\ w_n/w_1 & w_n/w_2 & \dots & 1 \end{bmatrix} \tag{1}$$

where w_1 is the weight of element 1, w_2 is the weight of element 2 and w_n is the weight of element n . Table 1 shows the relative importance of two elements that is rated using Saaty's 9-point scale (Saaty, 2008).

Pair-wise comparison matrix will be constructed based on the numerical value of the criteria, and the numerical data of each criteria, e.g. operating temperature, pressure, and extraction percentage, can be used directly in the matrix. When the numerical data is available, the pair-wise comparison matrices for minimization and maximization of problems can be constructed using Eq. (2) and (3), respectively (Sipahioglu, 2008).

$$A = \begin{bmatrix} 1 & w_2/w_1 & \dots & w_n/w_1 \\ w_1/w_2 & 1 & \dots & w_n/w_2 \\ \dots & \dots & \dots & \dots \\ w_1/w_n & w_2/w_n & \dots & 1 \end{bmatrix} \text{ (For minimization problems)} \tag{2}$$

$$A = \begin{bmatrix} 1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & 1 & \dots & w_2/w_n \\ \dots & \dots & \dots & \dots \\ w_n/w_1 & w_n/w_2 & \dots & 1 \end{bmatrix} \text{ (For maximization problems)} \tag{3}$$

Table 1
Fundamental scale of absolute numbers.

Intensity	Definition of Importance	Explanation
1	Equal	Two activities contribute equally to the objective
2	Weak or slight Moderate	Experience and judgment slightly favor one activity over another
3		
4	Moderate plus Strong	Experience and judgment strongly favor one activity over another
5		
6	Strong plus	An activity is favored very strongly over another; its dominance demonstrated in practice
7	Very strong	
8	Very, very strong	The evidence favoring one activity over another is of the highest possible order of affirmation
9	Extreme	
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it compared to activity j , then j has the reciprocal value when compared with i	
1.1–1.9	If the activities are very close	May be difficult to assign the best value; compared to other contrasting activities, the size of the small numbers would not be noticeable, yet they can still indicate the relative importance of the activities.

Table 2
Criteria and sub-criteria used in the AHP model.

Criteria	Sub-Criteria	Description
Leach Parameters (C ₁)	Acid Consumption (SC ₁)	The amount of acid consumption
	Temperature (SC ₂)	The temperature effect on extraction
	Leaching Time (SC ₃)	The duration of leaching
	Particle Size (SC ₄)	The particle size fraction
	Pressure (SC ₅)	The pressure effect on extraction
Extraction(C ₂)	Nickel (SC ₆)	The nickel extraction
	Cobalt (SC ₇)	The cobalt extraction
	Iron (SC ₈)	The iron extraction
	Initial Investment Cost (SC ₉)	Investment costs of operations tend to be significant and can be a major determining factor in the selection of an appropriate leaching method.

The eigenvector method is used to calculate the relative weights of the elements in each pair-wise comparison matrix. The relative weights of matrix *A* are obtained from the following equation:

$$(A - \lambda_{max} \times I) \times w = 0 \tag{4}$$

where λ_{max} is the largest eigenvalue of matrix *A* (Hwang & Yoon, 1981).

Saaty (1990) suggested utilizing the Consistency Index (*CI*) and the Consistency Ratio (*CR*) to verify the consistency of the comparison matrix. *CI* and *CR* are defined as follows:

$$CI = (\lambda_{max} - n) / (n - 1) \tag{5}$$

where *n* is the size of the matrix (Ishizaka & Labib, 2009).

$$CR = CI / RI \tag{6}$$

where *RI* represents Saaty's calculated random index measures for various sizes of matrix size (*n*). If the *CR* value is less than or equal to 0.10, comparisons made by a decision maker are considered acceptable. Larger values of *CR* require revision of the judgments of the decision maker. Local priorities of the elements of different levels are aggregated to obtain the final priorities of the alternatives in the last step of the AHP (Kursunoglu & Onder, 2015).

3.1. Development of the AHP model

It is essential to identify the factors that influence the selection of a leaching method. Three main criteria were identified as Leaching parameters, Extraction and Economical, each with specific sub-criteria. The main criteria and sub-criteria for the selection are summarized in Table 2. The first step in developing the AHP model is to develop a hierarchical structure of the decision-making problem. This classifies

the objective, all decision criteria and variables into three major levels. The top level represents the main objective of selecting a leaching method. Level 2 represents the main criteria and sub-criteria. Level 3 contains the decision alternatives that affect the selection process. Fig. 1 shows the hierarchy of the AHP model for the selection of an appropriate leaching method.

3.2. Pair-wise comparisons

The main aim of this study is to define which leaching method is the most compatible. The leaching method selection problem is divided into a hierarchical structure (Fig. 1). ExpertChoice® 2000 Software is used for pair-wise comparison matrices and sensitivity analysis. The pair-wise comparison matrices are shaped into the criteria by the experts. According to Saaty's nine-point scale as given in Table 1, the pair-wise comparison matrices are reciprocal (in assigning a value from 1 to 9 to the comparison matrix between the criteria *i* and *j*, the reciprocal value corresponds to the comparison between *j* and *i*). Calculation of λ_{max} , *CR* and *CI* is used with reference to the theoretical explanation given in Section 3. Similar steps are repeated for normalizing and determining of priorities of the other pair-wise comparison matrices, which are established for leaching method selection. *CR* values of pair-wise comparison matrices vary between 0 and 0.10 in the study. It can be summarized that all comparisons are consistent. Table 3 shows the pair-wise comparison matrix according to main criteria.

From the results summarized in Table 3, it is apparent that the Economical main criterion is the most important factor (priority value: 0.761), followed by the Leach Parameters and Extraction main criteria, respectively. Tables 4–5 illustrate the priority values of each sub-criterion. Particle Size is the most important sub-criterion with a score of 0.414 in the Leach Parameters main criterion; Nickel and Cobalt are the most important sub-criteria with a score of 0.474 in the Extraction main criterion.

Alternatives were compared pair-wise with respect to each of the sub-criteria. Tables 6–14 show the expert team's comparison of alter-

Table 3
Pair-wise comparison matrix according to main criteria.

	Leach parameters	Extraction	Economical	Local priorities
Leach parameters	1	3	1/6	0.166
Extraction	1/3	1	1/8	0.073
Economical	6	8	1	0.761
$\lambda_{max} = 0.07$				

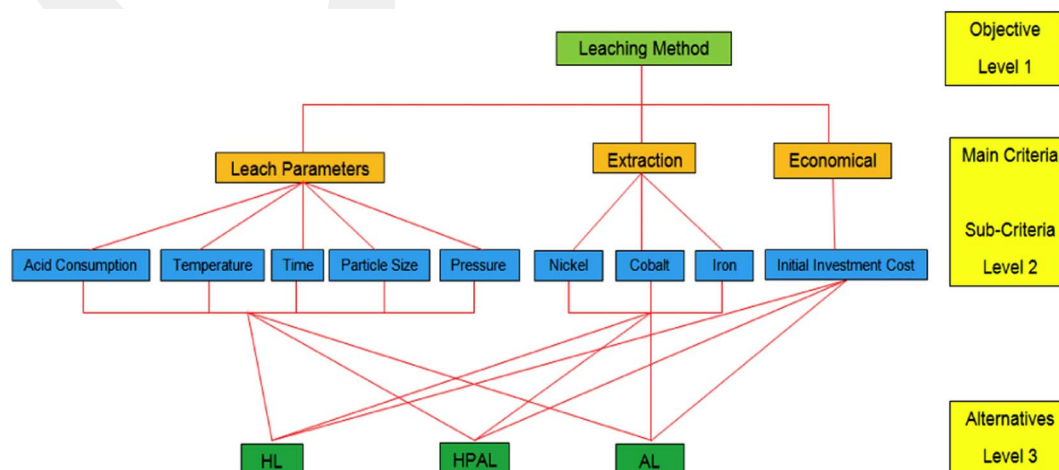


Fig. 1. The hierarchy of the AHP model for the selection of an appropriate leaching method.

Table 4
Comparison of sub-criteria with respect to the “Leach Parameters” criteria.

	Temperature	Leaching time	Acid consumption	Particle size	Pressure	Local priorities
Temperature	1	5	3	1/2	2	0.255
Leaching time	1/5	1	1/5	1/5	1/5	0.044
Acid consumption	1/3	5	1	1/5	1/3	0.104
Particle size	2	5	5	1	3	0.414
Pressure	1/2	5	3	1/3	1	0.184
$\lambda_{\max} = 0.08$						

Table 5
Comparison of sub-criteria with respect to the “Extraction” criteria.

	Nickel	Cobalt	Iron	Local priorities
Nickel	1	1	9	0.474
Cobalt	1	1	9	0.474
Iron	1/9	1/9	1	0.053
$\lambda_{\max} = 0.00$				

Table 6
Comparisons of the alternatives with respect to “temperature” sub-criteria.

	HL	HPAL	AL	Local Priorities
HL	1	9	1	0.474
HPAL	1/9	1	1/9	0.053
AL	1	9	1	0.474
$\lambda_{\max} = 0.00$				

Table 7
Comparisons of the alternatives with respect to “leaching time” sub-criteria.

	HL	HPAL	AL	Local Priorities
HL	1	1/9	1/7	0.055
HPAL	9	1	3	0.655
AL	7	1/3	1	0.290
$\lambda_{\max} = 0.08$				

Table 8
Comparisons of the alternatives with respect to “acid consumption” sub-criteria.

	HL	HPAL	AL	Local Priorities
HL	1	1/2	7	0.346
HPAL	2	1	9	0.597
AL	1/7	1/9	1	0.057
$\lambda_{\max} = 0.02$				

Table 9
Comparisons of the alternatives with respect to “particle size” sub-criteria.

	HL	HPAL	AL	Local Priorities
HL	1	7	9	0.793
HPAL	1/7	1	2	0.131
AL	1/9	1/2	1	0.076
$\lambda_{\max} = 0.02$				

natives against each of the sub-criteria.

The outcome is shown in Fig. 2. It is concluded from Fig. 2 that HL, with a rating of 0.592, is the most preferred, followed by AL and HPAL. The percentage priorities of HL, AL and HPAL are 59.20%, 29.30% and

Table 10
Comparisons of the alternatives with respect to “pressure” sub-criteria.

	HL	HPAL	AL	Local Priorities
HL	1	9	1	0.474
HPAL	1/9	1	1/9	0.053
AL	1	9	1	0.474
$\lambda_{\max} = 0.00$				

Table 11
Comparisons of the alternatives with respect to “nickel” sub-criteria.

	HL	HPAL	AL	Local Priorities
HL	1	1/4	1/3	0.122
HPAL	4	1	2	0.558
AL	3	1/2	1	0.320
$\lambda_{\max} = 0.02$				

Table 12
Comparisons of the alternatives with respect to “cobalt” sub-criteria.

	HL	HPAL	AL	Local priorities
HL	1	1/4	1/3	0.122
HPAL	4	1	2	0.558
AL	3	1/2	1	0.320
$\lambda_{\max} = 0.02$				

Table 13
Comparisons of the alternatives with respect to “iron” sub-criteria.

	HL	HPAL	AL	Local priorities
HL	1	1/6	4	0.176
HPAL	6	1	9	0.763
AL	1/4	1/9	1	0.061
$\lambda_{\max} = 0.10$				

Table 14
Comparisons of the alternatives with respect to “initial investment cost” sub-criteria.

	HL	HPAL	AL	Local priorities
HL	1	9	3	0.655
HPAL	1/9	1	1/7	0.055
AL	1/3	7	1	0.290
$\lambda_{\max} = 0.08$				

11.50%, respectively.

The performance graph (Fig. 3) shows the priorities of the final alternatives with regard to the main criteria. If the Leach Parameters and Economical main criteria are considered, HL is preferable to AL and

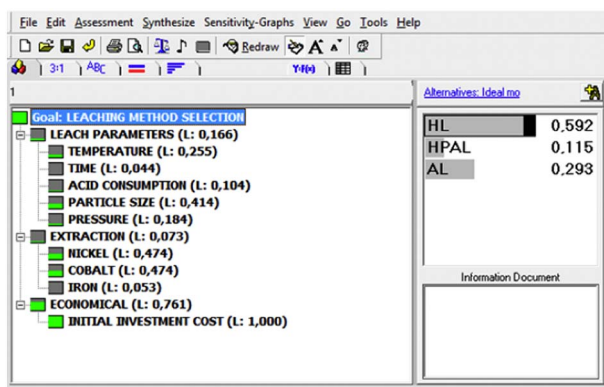


Fig. 2. Outcome of the selection of the leaching method.

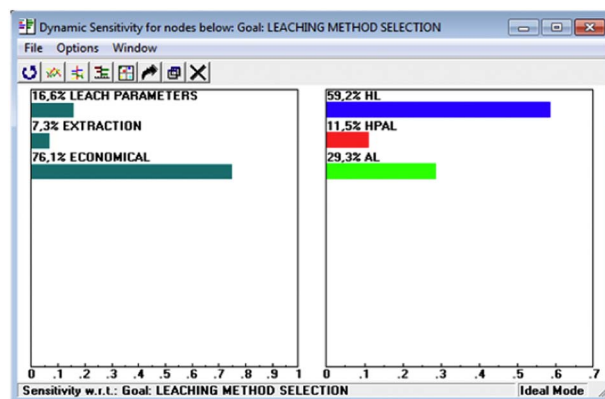


Fig. 4. Main criteria and dynamic sensitivity.

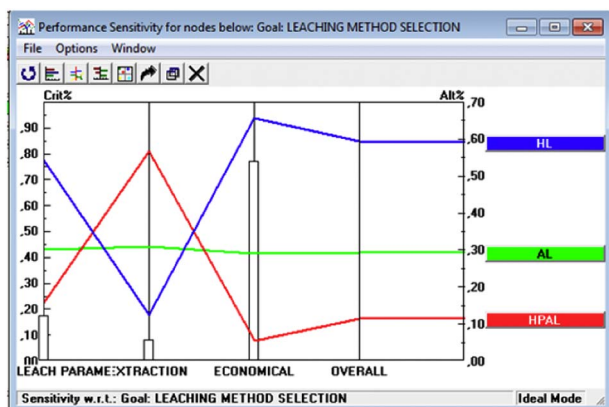


Fig. 3. Performance graph of the leaching method considered.

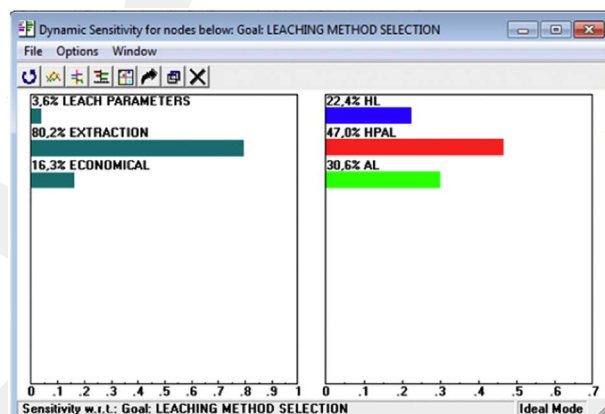


Fig. 5. Main criteria and dynamic sensitivity changes.

HPAL. If the Extraction main criteria are considered, HPAL is preferable to HL and AL.

3.3. Sensitivity analysis

Sensitivity analyses are performed by decision makers to analyse the elasticity of the final decision. The final priorities of the alternatives are highly dependent on the weights attached to the main criteria which are based on the subjective judgements of the decision maker. Small changes in the relative weights can cause major changes of the final ranking, and given the subjective nature of the judgment, the stability of the ranking under varying criteria weights must be tested. Sensitivity analysis is therefore performed based on scenarios that reflect alternative future developments or different views on the relative importance of the criteria. Through increasing or decreasing the weight of individual criteria, the resulting changes of the priorities and the ranking of the alternatives can be observed. Sensitivity analysis hence provides information on the stability of the ranking and can be used to determine the impact of the main criteria on the alternative leaching methods. For this purpose, the weights of the important criteria are separately altered, simulating weights between 0% and 100%.

One of the most important properties of ExpertChoice® 2000 Software is that it can provide the sensitivity analysis on the problem. The main criteria and dynamic sensitivity are shown in Figs. 4 and 5 and the performance of each alternative are presented as coloured bars and numerical values. As can be seen from Figs. 4 and 5, when the weight of extraction criteria increased from 7.3% to 80.2%, the economical criteria decreased from 76.1% to 16.3% and the weight of leach parameters criteria decreased from 16.6% to 3.6%. These changes result in the decrease of HL performance in the model from 59.2% to 22.4%, while HPAL and AL are increased from 11.5% to 47.0% and from 29.3% to 30.6%, respectively. Changes such as shown

in these scenarios may be attributed to the global economical conditions. For example, when the prices of nickel and cobalt are low, the initial investment cost of the leaching plant is likely to be determined as the most important aspect in selecting the method, which is the case in the present study; however, if the prices of the commodity are very high, the decision maker may increase the weight of the extraction criteria which will lead to the increase in the HPAL performance in the model.

4. Conclusions

This paper has demonstrated the application of the AHP technique in hydrometallurgical operations. It was seen that it is possible to select the most appropriate leaching method in a more scientific way using the AHP. The method is flexible and transparent, and also easy to apply by decision makers. In the presented AHP model, three alternatives (i.e. HL, HPAL and AL) were evaluated with reference to three main criteria and sub-criteria. The evaluation revealed that decision makers pay more attention to economical main criteria than other two main criteria. The AHP results show that HL is determined as the most appropriate leaching method for the lateritic nickel ore. In addition, the AHP results were analysed using sensitivity analysis. The sensitivity analyses show that the rankings of alternatives transform from HL to HPAL when the economical main criteria decreases from 76.1% to 16.3%. Based on the software results, HL was selected as the most attractive leaching method for Caldag lateritic nickel ore.

Acknowledgements

We thank Nilufer Kursunoglu, a PhD Candidate in Mining Engineering from Eskisehir Osmangazi University, for her valuable

contribution and for proofreading the manuscript.

References

- Adebimpe, R.A., Akande, J.M., Arum, C., 2013. Mine equipment selection for Ajabanoko iron ore deposit, Kogi State, Nigeria. *Sci. Res.* 1 (2), 25–30.
- Alpay, S., Yavuz, M., 2009. Underground mining method selection by decision making tools. *Tunn. Undergr. Space Technol.* 24, 173–184.
- Bhushan, N., Rai, K., 2004. Strategic decision making: applying the analytic hierarchy process. *Spring* 11–15.
- Hwang, C.L., Yoon, K.L., 1981. *Multiple Attribute Decision Making: Methods and Applications*. Springer-Verlag, New York, pp. 2–4.
- Ishizaka, A., Labib, A., 2009. Analytic hierarchy process and expert choice: benefits and limitations. *ORInsight* 22 (4), 201–220.
- Kursunoglu, S., Kaya, M., 2016. Atmospheric pressure acid leaching of Caldag lateritic nickel ore. *Int. J. Miner. Process.* 150, 1–8.
- Kursunoglu, N., Onder, M., 2015. Selection of an appropriate fan for an underground coal mine using the analytic hierarchy process. *Tunn. Undergr. Space Technol.* 48, 101–109.
- Kyle, J., 2010. Nickel laterite processing Technologies-where to next? In: *Alta 2010 Nickel/Cobalt/Copper Conference*, 24–27 May, (Perth, Western Australia).
- Mohsen, S., Mohammad, A., Reza, K., Mohammad, K., 2010. Mineral processing plant location using the analytic hierarchy process—a case study: the Sangan iron ore mine (Phase 1). *Min. Sci. Technol.* 20, 691–695.
- Onal, M.A.R., Topkaya, Y.A., 2014. Pressure acid leaching of Çaldağ lateritic nickel ore: an alternative to heap leaching. *Hydrometallurgy* 142, 98–107.
- Owusu-Mensah, F., Musingwini, C., 2010. Evaluation of ore transport options from Kwesi Mensah shaft to the mill at the Obuasi mine. *Int. J. Min. Reclam. Environ.* 25, 109–125.
- Oxley, A., Sirvanci, N., Purkiss, S., 2007. Caldag Nickel Laterite Atmospheric Heap Leach Project. 13. Association of Metallurgical Engineers of Serbiapp. 5–10.
- Saaty, T.L., 1977. A scaling method for priorities in hierarchical structures. *J. Math. Psychol.* 15, 234–281.
- Saaty, T.L., 1990. How to make a decision: the analytic hierarchy process. *Eur. J. Oper. Res.* 48 (1), 9–26.
- Saaty, T.L., 1999. Basic theory of the analytic hierarchy process: how to make a decision. *Rev. R. Acad. Cienc. Exact. Fis. Nat.* 93, 406–407.
- Saaty, T.L., 2008. Decision making with the analytic hierarchy process. *Int. J. Serv. Sci.* 1, 83–86.
- Sipahioglu, A., 2008. *Analytical Hierarchy Process*. Eskisehir Osmangazi University (Unpublished lecture notes).
- Zoran, D., Sasa, M., Dragi, P., 2011. Application of the AHP method for selection of a transportation system in mine planning. *Underground Mining Eng.* 19, 93–99.