# Hybrid method for selection of the optimal process of leachate treatment in waste plants

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**ABSTRACT**

Leachate from landfill waste plants is a very complex and highly contaminated liquid. In its composition we find dissolved organic matter, inorganic salts, heavy metals and other xenobiotic organic compounds, so it can be toxic, carcinogenic and capable of inducing a potential risk to biota and humans. European law does not allow such leachate to leave the premises without being depurated. There are many procedures that enable debugging, always combining different techniques. Choosing the best method to use in each case is a complex decision, as it depends on many tangible and intangible factors that must be weighed to achieve a balance between technical, cost, and environmental sustainability. We present a hybrid method for choosing the optimal combination of techniques to apply in each case, by combining a multi-criteria hierarchical analysis based on expert data obtained by the Delphi method with an analysis by the method of VIKOR to reach a consensus solution.

**KEYWORDS**

Leachate treatment; Waste plants; Analytical Hierarchy Process; Delphi method; VIKOR technique.

## 1. Introduction

European Union Council Directive 1999/31/EC establishes the obligation of controlling the water, managing leachate, minimizing the rainwater that penetrates into the landfills and keeping the superficial or underground waters from penetrating into the waste and collecting whatever might percolate for its correct treatment for further use or spill. Waste treatment plants, whether urban or industrial, deposit waste from their processes in landfills or controlled deposits. In all cases, leachate is created due to the self-decomposition of the waste deposited there, together with water supplied by rain and water runoff. This water percolates inside the landfill and accumulates at the bottom, diluting and dragging in its way numerous components, like volatile and organic compounds, nitrogen compounds, heavy metals and any other constituent that may be contained in the residue or the land where the landfill is located. Not all landfills are equal; they do not contain the same type of waste as they are located in different climatic and geological areas and, therefore, are subject to different external actions, which characterize the leachate that inevitably occurs in all of them. In short, the landfill leachate is a complex and highly contaminated wastewater (Kjeldsen et al. 2002), with dissolved organic matter, inorganic salts, heavy metals and xenobiotic organic compounds which could be toxic and carcinogenic and able to induce potential risk for biota and humans. The lack of quality is the result of biological, chemical and physical processes in the landfills, along with the specific waste composition and landfill water regime. If this leachate goes unchecked out from the landfill, it will surely cause a major impact on the environment, polluting the land and, more importantly, the aquifers around the landfill (Yang et al. 2013).Waste production, urban and industrial, has grown considerably with the increase in population and living standards, so the problem of leachate purification has increased exponentially (Chen et al. 2013). Moreover, it is a part of European Union policy to achieve a high level of health and environmental protection, and one of the objectives to be pursued is sustainable development. Underground space is an environmental entity and a natural resource in its own right what can be damaged or changed by human activities (Curiel-Esparza and Canto-Perello 2012).

There are different methods to remove or purge the leachate generated in the landfill permanently, adapting to the traits of each of them (Abbas et al. 2009). In many cases, plants that are currently in operation treating leachate combine several of the above treatment methods to meet the constraints for the effluent concentrations (van Praag et al. 2009; Grupta et al. 2007). Moreover, there is a wide range of possible combinations of these leachate treatment methods; therefore, selecting the best method in each case results in a complex process of analyzing these technical treatments. This research work presents an expert system to select the optimal procedure for treatment and purification of leachate from waste plants. In addition, establishing a set of criteria is a key factor for choosing amongst the number of technically feasible treatment methods. Different criteria can be used depending on the specific characteristics of each leachate, the plant's capacity, the technologies applied and the legal limits of the resulting final waste discharge (Ritzkowski and Stegmann 2012). The methodology used will let us assign different weights for the criteria tailored to each particular project, in order to consider the complexity of this decision making problem.

The expert system proposed is a hybrid method combining the Analytical Hierarchy Process (AHP) with the Delphi method and the VIKOR technique. The environmental engineer carries out pairwise comparison judgments which are then used to develop overall priorities for ranking the technical treatments. The different criteria implemented will be cost, leachate and effluent characteristics together with environmental impact. All of them, with their different weights, will be analyzed in relation to the possible treatment to implement. The AHP analyses a theory of relative measurement on absolute scales capable of dealing with intangible criteria and based on paired comparison judgment of knowledgeable experts (Saaty, T.L. 1980; Ozdemir and Saaty 2006; Lee and Chan 2008; Syamsuddin 2010; Thapa and Murayama 2010; Zavadskas et al. 2011). How to measure intangibles is the main concern of the mathematical processes of the AHP as this paper will show. Experience gathered over the years with the AHP methodology in a wide variety of decision-making areas shows that it is suitable for structuring relevant knowledge concerning consensus in complex multicriteria problems. The Delphi technique is well suited as a means and method for consensus-building by using a series of questionnaires to collect data from a panel of selected experts (Hsu and Sandord 2007; Roubelat 2011; Gracht 2012). The Delphi technique is performed to facilitate an efficient panel of experts' dynamic process. Finally, the VIKOR method finds a compromise solution in decision problems with conflicting and non-commensurable criteria that is the closest to the ideal (Mela et al. 2012; San Cristobal 2012; Lee 2013). The alternatives are evaluated according to all established criteria. And the achieved compromise solution provides a maximum utility of the majority, and a minimum individual regret of the opponent.

## 2. Defining hierarchy structure

To overcome the lack of tangible data and the use of intangible criteria, AHP–Delphi model will be applied to make progress in leachate purification. Integrating the AHP with a Delphi process provides an environmental engineer with a systematic approach to evaluate multi-criteria and multi-alternative problems requiring judgments involving intangible characteristics (Canto-Perello et al. 2013).

The AHP multicriteria analysis is a mathematical method that can be used for the selection of the best from the many options considered (Saaty 1980).

To search for a solution it is necessary to consider a set of criteria that fit the problem and to evaluate the different options. It often happens that the criteria are considered to represent goals that are sometimes conflicting and even contradictory. For example, it may be that the cheapest solution is not the most reliable. Therefore, the final selection is always a compromise based on the relative weights assigned to the individual criteria (Statnikova et al. 2005; Bréchet and Tulkens 2009). We try to quantify the relative priorities for a given set of alternatives, using a ratio scale, based on the opinion of each expert, or person who makes the decisions, emphasizing the importance of intuitive judgments made in a decision-making process and consistency of responses in the comparison of alternatives (Saaty 2001). The strength of this approach is that it organizes tangible and intangible factors in a systematic way, and provides a structured yet relatively simple solution to the decision-making problems (Curiel-Esparza and Canto-Perello 2013). Through this process, a large problem is decomposed into multiple simple pairs of issues, so that going down in gradual steps, we will be able to prioritize all proposed solutions to the problem.

The Delphi method is based on the opinions of experts on the underlying problem and provides aggregated results. This method aims to gather on one hand the views of experts on a particular topic, and on the other hand, intends that each of these experts react to the views of other colleagues. In the first phase of Delphi, alternatives and criteria are explored and discussed among experts. To achieve this goal, an anonymous questionnaire was sent in two phases, the second phase adjusted to the results obtained from the first. It is not intended that experts face each other, but it comes to studying the convergence of views on the question asked. The questionnaire and the experts differ by sector. The participatory aspect is not included in this method mainly because it tries to identify the convergences of opinion among experts, especially avoiding any possible source of discord or conflict.

Criteria and alternatives that get fewer consensus among experts will be eliminated. Proper selection of the criteria is a decisive factor for the development of this procedure. To understand the process, a brief description of the technical treatments and criteria selected follows.

Nowadays, the treatment of leachate coming from sewage deposits is made by ways of different procedures, in one or several stages. Leachate treatment can be compiled into five groups (Renou et al. 2008; Li et al. 2010; Heyer et al. 2005):

- Leachate recycling.
- Combined treatment with municipal waste waters.
- Aerobic and anaerobic biotreatments.
- Physical and chemical methods such as sedimentation/floatation, air separation, adsorption, chemical precipitation and oxidation.
- Treatments based on membranes, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO).

The characteristics of landfill leachate vary depending on the type of waste deposited, the degree of stabilization, site hydrology, moisture content, seasonal climate variations, age of landfill, and the state of decomposition in the landfill (Wang et al. 2003). Young leachates contain high amounts of volatile fatty acids with a high ratio of biological oxygen demand / chemical oxygen demand (BOD/COD) and are easier to treat than mature landfill leachate, as it contains a fraction of organic compounds with high resistance to biological treatments (Ahn et al. 2002; Abood et al. 2013).So, if we want to fulfill the requirements of effluent discharges, treatment of leachate can be both complicated and expensive. Furthermore, leachate depuration process can bring about changes in the properties of the resulting sludge that increase the toxicity (Chiochetta et al. 2014). It is necessary to combine physical, chemical and biological methods as it is hard to achieve satisfactory treatment efficiencies and to resolve all of the leachate polluting parameters using any of these methods separately. The technology of combined treatment improves the quality of the effluents and minimizes the residue obtained to a treatment cost under those obtained from individual treatment methods (Li et al. 2010). It is necessary to combine, attending to a series of pre-established criteria, a series of procedures known, studied and contrasted in multiple installations procedures to obtain treatment alternatives capable of eliminating the polluting charge in the leachate generated in waste treatment plants. The only valid technologies considered should be those which fulfill the legal aspects in terms of effluent quality (Heyer et al. 2005). In this paper the following technical treatments have been considered:

Biological treatment + physicochemical + activated carbon (BPA): A combination of successive treatments, through a biological process (generally aerobic)that will remove part of the organic matter, followed by a physicochemical treatment that removes the non-biodegradable part of the leachate and precipitates any heavy metals found in it (Vedaraman et al. 2013). It is completed by a process of adsorption in an activated carbon filter that allows the removal of great part of the COD and the ammonium nitrate.

Biological treatment + physico-chemical + reverse osmosis (BPR): A combination of successive treatments, through a biological process (generally aerobic) that will remove part of the organic matter, followed by a physico-chemical treatment that removes the non-biodegradable part of the leachate and precipitates any heavy metals found in it. It is completed by the passing of the leachate through some high-pressure membranes, in one or two stages, separating colloidal particles, low-molecular-mass particles and soluble salts (Zhang et al. 2013).

Biological treatment + chemical oxidation ($O_3$ + UV) + ultrafiltration+ activated carbon (BCU): A combination of successive treatments, through a biological process (generally aerobic) that will remove part of the organic matter, followed by a chemical oxidation, by addition of ozone and ultraviolet rays (UV) (Chen et al. 2013), followed by an ultrafiltration to concentrate suspended solids, high-molecular-mass soluble solids, macromolecules and other particles (Ersahin et al. 2013). The process ends with a process of adsorption in an activated carbon filter that allows the removal of great part of the COD and the ammonium nitrate.

Lagooning (LAG): A combination of aerobic, anaerobic and maturing lagoons. They are based on the usage of herbaceous, rhizomes and macrophyte plants, like canes, or tree species like willows, for the natural biological purification of leachate (Grisey et al. 2012). This method requires high retention times, long enough so that you can develop as much bacteria as possible so that it degrades the organic fraction. The operation costs and maintenance are relatively low.

Fermentative treatment (FER): It can be either aerobic or anaerobic. In the first case, organic matter is decomposed at high speed through an oxygen supply. There are small retention times. Elimination percentages are stimulated by oxygen supply. In anaerobic fermentation, organic matter decomposition is carried out without oxygen, increasing the time taken for the decomposition, with more time spent within the reactor, but purifying high loads of pollutant in the influent. That will allow the resulting product to be used as liquid fertilizer (Romero et al. 2013).

Forced evaporation (FEV): Evaporation of the liquid state of the leachate through heat supply, meaning that these techniques are a separation in a clean water and a solid phase which includes all pollution material. Normally the condensate vapors contain volatile components and the solids are pulpy. It produces a dry concentrated sludge, potentially classified as a dangerous residue. The predominant components in effluent of evaporation plants are volatile, sometimes chlorinated organics and ammonium. Often it is necessary additional treatment steps (Boopathy et al. 2013; Chiumenti et al. 2013).

We have not considered the possibility of recirculation of leachate in the landfill, because the long-term sustainability and environmental impacts of such a practice remain disputed and must be verified (Xing et al. 2013). We can use different criteria depending on the specific characteristics of each leachate, the plant's capacity, the technologies applied, the sustainable strategies and the objective of the analysis (Curiel-Esparza et al. 2004).The criteria employed in this research work are grouped into four categories:

Cost of the treatment (COS): This criterion takes into account the costs of building, installation of electromechanical machinery and land obtaining as well as the operation, maintenance and the management of the effluent costs.

Leachate treated (LEA): It analyses the quantity and quality of the leachate generated by the plant or the associated landfill, in relation to the size of the installation and the processes that can be implemented.

Effluent obtained after de purification process (EFF): It considers the quantity of effluent generated by the purifying plant in relation with its spillage system as well as the requirements of the parameters of spillage in relation to this being done into public rivers or conventional sanitary systems.

Impact on the environment made by the purification installations (ENV): It reviews the environmental impact made by the size of the purifying plant in relation to the flow purified as well as the negative effects on the environment generated and the ability to restore the renewable resources.

At the same time, each of these criteria can be decomposed into a series of sub criteria (see Figure 1) in the following way:

Facilities (FAC): This sub criterion studies the costs of building, installation of electromechanical systems and obtaining of land.

Operation and maintenance costs (O&M): It comprises the operation and maintenance costs of the plant (personnel, specific energy demand, reagent, sludge production, material, equipment, administrative, etc.).

Resulting waste treatment cost (RWT): This sub criterion takes into account costs originated from the treatment of the resulting residue after the purifying operations which in some cases are considered as dangerous residues.

Leachate quantity (LQN): It analyses the quantity of leachate generated by the plant or the associated landfill, in relation to the size of the installation and the processes that may be implemented.

Leachate quality (LQL): This sub criterion reviews the parameters of contamination in the leachate generated by the plant or the landfill associated in relation with the grade of maturation of the landfill, and if it is a leachate from municipal solid waste or industrial leaching.

Quantity of effluent produced (EQN): It considers the amount of effluent generated by the purification plant related to the spilling system of it.

Quality of the effluent (EQL): This sub criterion studies the requirements of the parameters of spillage relating it to this being in a public river or conventional sanitary systems.

Size of the installation (INS): It analyses the environmental impact caused by the size of the depuration plant related to flow it purifies.

Odors (ODO): This sub criterion considers the environmental impact made by the smell that can be generated around the purification plant.

Noise (NOI): It takes into account the impact generated by the noise around the purification plant on the environment.

Taking into account all these requirements and following the initial step of AHP (Saaty 2008) the goal is decomposed into a hierarchy structure shown in Figure1. Obviously, the criteria and technical treatments to be used by any community will be tailored to local needs.

## 3. Second questionnaire and construction of pairwise comparison matrix for the criteria

According to the Delphi process, it is necessary to send to experts a second questionnaire for evaluating the main criteria. In the Delphi process, the expert panel interacts with anonymous comments, while the AHP method is used to obtain a general decision made up of smaller decision components. As an example, using a 9-point scale (see Table 1), Table 2 shows a particular questionnaire for evaluating criteria with respect to the overall goal. This scale has been developed over time by Saaty, contrasting its effectiveness not only in many applications, but also through theoretical comparisons with many other scales (Saaty 2012). Each expert performed a pairwise comparison to indicate its preference for each criterion. Table 3 shows a particular questionnaire for evaluating sub criteria with respect to the overall goal, under the terms of each criterion. As a result, a matrix evaluating results of the criteria with respect to the overall goal is obtained (see Table 4). Pairwise comparison matrix for the criteria is constructed using the mean value obtained from Table 4. In the same way, Table 5 shows this pairwise comparison for sub criteria.

## 4. Priority weighting of the criteria and sub criteria. Consistency Ratio

In the Analytic Hierarchy Process (AHP), multiplicative preference relations are called judgment matrices, and are adopted to express the decision makers' preferences. Many researchers focus on the selection model in AHP group decision making (i.e., aggregation rules and prioritization methods). In this paper we use the aggregation of individual judgments (AIJ), where the weighted geometric mean method (WGM) is generally used (Dong et al. 2010). Treating the group as a new individual with AIJ requires satisfaction of the reciprocity condition for the judgments. It has been demonstrated that WGM is indeed the only method which preserves the reciprocally symmetric structure of the judgment matrices and satisfies the Pareto Principle over judgments and the so-called homogeneity condition. Other methods or procedures, like the arithmetic mean, do not guarantee it (Bernasconi et al. 2014). For AIJ, the decision makers use the weighted geometric mean method to aggregate individual judgment matrices to obtain a collective judgment matrix, $A^{(c)} = (a_{ij}^{(c)})_{n\times n}$, where

$$a_{ij} = \prod_{k=1}^{m} \left(a_{ij}^{(k)}\right)^{1/k} \qquad (1)$$

The relative priority of each individual criterion will be determined after developing the pairwise comparison matrix for the criteria (A).The principal eigenvector of this matrix is the desired priority vector ω according to Saaty. To find this priority vector, the linear system $A\,\omega = \lambda\,\omega$ must be solved

$$\det (A - \lambda I) = 0 \qquad (2)$$

As discussed above, we have consulted a number of experts about the comparison between pairs of criteria and sub criteria. The expert system uses data obtained from inquiries made to experts, searching for correct and consistent information that allows us to make the best decision. Their knowledge and experience of the problem helps them to identify and set priorities with non-commensurable criteria. Geometric mean columns have been obtained as detailed in previous paragraphs, to aggregate individual judgment matrices to obtain a collective judgment matrix. These values are incorporated in the pairwise comparison matrices. For criteria evaluation, the aggregated matrix for criteria, with its eigenvector, is shown below:

$$A = \begin{bmatrix} 1.0000 & 1.8080 & 0.7582 & 1.6105 \\ 0.5531 & 1.0000 & 0.3975 & 1.0475 \\ 1.3189 & 2.5155 & 1.0000 & 3.4270 \\ 0.6209 & 0.9546 & 0.2918 & 1.0000 \end{bmatrix} \qquad (3)$$

$$\omega = \begin{bmatrix} 0.2774 & 0.1569 & 0.4186 & 0.1471 \end{bmatrix} \qquad (4)$$

Hierarchical synthesis is now used to weight the eigenvectors by the weights of the criteria and the sum is taken over all weighted eigenvector entries corresponding to those in the immediately lower level of the hierarchy. Having made all the pair-wise comparisons, the consistency is determined by using the eigenvalue, $\lambda_{max}$, to calculate the consistency index, CI as follows:

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)} \qquad (5)$$

where n is the matrix size, or the number of evaluated criteria. Judgment consistency can be checked by taking the consistency ratio (CR). The calculation of the Consistency Rate is given by the formula CR = CI/RI, where RI value is fixed and is based on the number of evaluated criteria, as shown on Table 6.

Maximum CR is 0.05 for order of matrix (n) equal than three and 0.10 for n=5 or more. If it is more, the judgment matrix is inconsistent. For a consistent matrix, judgments should be reviewed by experts, even improved. All steps are performed for all levels in the hierarchy. In our case, for the criteria matrix, $\lambda_{max}$ = 4.0205, CI = 0.0068 and CR = 0.0077< 0.05, so that the consistence condition is satisfied.

For Sub-criteria Evaluation, we obtain four matrices with their respective eigenvectors, such as those corresponding to sub criterion COS, showed below:

$$A = \begin{bmatrix} 1.0000 & 0.2685 & 0.2988 \\ 3.7246 & 1.0000 & 1.4911 \\ 3.3471 & 0.6707 & 1.0000 \end{bmatrix} \quad (6)$$

$$\omega = [0.0341 \quad 0.1399 \quad 0.1034] \quad (7)$$

In this case, the values of $\lambda_{max}$, CI and CR are, respectively, $\lambda_{max}$ = 3.0095, CI = 0.0048, CR = 0.0092< 0.05, and the consistence condition is satisfied.

## 5. Third questionnaire and evaluate technical treatments according to criteria an sub criteria

After evaluating the weight of each criterion and sub criterion, we proceed to calculate the priority of each alternative with respect to each sub criterion. It sends a third questionnaire to the experts to evaluate the technical treatments. Each expert will conduct a pairwise comparison to indicate their preference for each alternative. Then, a pairwise comparison matrix for the technical treatments is constructed using the geometric mean value obtained from experts by the AIP method. As in previous steps, the eigenvector method has been applied to obtain the priority vector, and a consistency analysis is performed for each case. For alternative evaluation, we obtain ten matrices with their corresponding eigenvectors. For example, Table 7 shows the pairwise matrix for sub criterion FAC, and its respective eigenvector.

We can obtain the matrix of technical treatments and the matrix of sub criteria vector (see Table 8 and Table 9), that we need to begin the next point, the application of VIKOR Method.

## 6. Achieving compromise solution with VIKOR Method

The VIKOR method is a multicriteria decision making developed by Serafim Opricovic (Duckstein and Opricovic 1980). This method is based on an aggregating function representing closeness to the ideal. The VIKOR method classifies the various alternatives so that most of the group obtains their highest utility and minimal individual repentance for the rest. Assuming that the alternatives are been evaluated according to each criterion function, the compromise ranking can be performed by comparing the measure of closeness to the ideal alternative (Sayadi et al. 2009). VIKOR method ranks alternatives and determines the solution named compromise that is the closest to the ideal. The problem is stated as follows: Determine the best (compromise) solution in multicriteria sense from the set of J feasible alternatives $A_1$, $A_2$, …, $A_j$, evaluated according to the set of n criterion functions. The input data are the elements $f_{ij}$ of the performance (decision) matrix, where $f_{ij}$ is the value of the $i^{th}$ criterion function for the alternative $A_j$. The VIKOR procedure has the following steps:

Determine the best $f_j^*$ and the worst values $f_j^-$ of all criteria ratings *j* = 1, 2 ... *n.*

$$f_j^* = max_i\{x_{ij}\} \quad (8)$$

$$f_j^- = min_i\{x_{ij}\} \quad (9)$$

Compute the values $S_i$ and $R_i$ using the following equations

$$S_i = \sum_{j=1}^{n} w_j \frac{f_j^* - x_{ij}}{f_j^* - f_j^-} \quad (10)$$

$$R_i = max_j w_j \frac{f_j^* - x_{ij}}{f_j^* - f_j^-} \quad (11)$$

Compute the values $Q_i$ as following

$$Q_i = \gamma \frac{S_i - S^*}{S^- - S^*} + (1-\gamma)\frac{R_i - R^*}{R^- - R^*} \quad (12)$$

where

$$S^* = min_i S_i$$

$$S^- = max_i S_i$$

$$R^* = min_i R_i$$

$$R^- = max_i R_i$$

and $\gamma$ is the weight for the strategy of maximum group utility and 1-$\gamma$ is the weight of the individual regret.

Rank the alternatives, sorted by the values *S, R* and *Q* in ascending order.

Propose the alternative ($A^{(1)}$) as a compromise solution, which is ranked as the best by the value of *Q* (minimum) if the following two conditions are satisfied:

Condition 1: Acceptable advantage

$$Q(A^{(2)}) - Q(A^{(1)}) \geq DQ \quad (13)$$

Where $A^{(2)}$ is the alternative found in second position in the ranking list by *Q,* and *DQ* = 1/(*J*-1).

Condition 2: Acceptable stability in decision making

The alternative $A^{(1)}$ must also be the best ranked by *S* and/or *R*. The compromise solution is stable within a decision making process, which could be the strategy of maximum group utility (when γ > 0.5 is needed), or —by consensus γ ~ 0.5, or "with veto" (γ <0.5). Please note that γ is the weight of the decision making strategy of maximum group utility.

If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of:

- Alternatives $A^{(1)}$ and $A^{2)}$ if only the condition C2 is not satisfied, or
- Alternatives $A^{(1)}$, $A^{(2)}$,..., $A^{(M)}$if the condition C1 is not satisfied; $A^{(M)}$is determined by the relation Q (A $^{(M)}$) – Q($A^{(1)}$)<*DQ* for maximum M (the position of these alternatives are "in closeness").

The obtained compromise solution could be accepted by the decision makers because it provides a maximum utility of the majority (represented by min S), and a minimum individual regret of the opponent (represented by min R). The measures S and R are integrated into Q for a compromise solution, the base for an agreement established by mutual concessions. In our case, we will compute the best $f_j^*$ and the worst $f_j^-$for all sub criteria, and we will obtain the results showing in Table 10. Table 11 presents the $S_i$, $R_i$ and $Q_i$ values for all technical treatments computed, obtained by using the equations previously showed. Table 12 shows the best S*and R*, and the worst $S^-$and $R^-$ for all technical treatments.

It can be seen from the results of Table 13, that the alternative BCU is the best ranked by the Qi value (minimum). We now check it for the following two conditions previously showed.

Condition 1.- Acceptable advantage test.

In our case, QA (1) = 0.00000, QA (2) = 0.13748, and according to the formula (13), QA (2)-QA (1) = 0.13748. So, J = 6, DQ = 0.20000, and QA (2)-QA (1) ≤ DQ, and the acceptable advantage test is not satisfied. Both technical treatments, BCU and BPR, are "in closeness".

Condition 2.- Acceptable stability in decision making:

Acceptable stability test is satisfied, because the best alternative for Q, BCU, is also the best ranked by S and R (considering the "by consensus rule γ ≈ 0.5"), and it is finally chosen and ranked the best one from the leachate depuration options.

## 7. Conclusions

Leachate is a complex and hazardous liquid. In its composition, heavy metals, suspended solids, soluble salts and others pollutants appear. It is necessary to purify it to avoid contamination of subsoil and aquifers near to landfills. The design of this purification treatment is a complicated decision due to the different incommensurable factors that exist in the election. Moreover, it is necessary to combine different techniques chosen from those that have been developed over time, taking into account the experience of the engineer who must implement them. This paper provides a procedure based in the Analytic Hierarchy Process, relying on the Delphi and VIKOR methods, to select the optimal technique for the purification of leachate.

Unlike the conventional AHP method, which provides weights for each of the proposed alternatives, the VIKOR method provides a stable solution and commitment among the experts consulted. The use of the Delphi method allows interaction between the different participants in the weighing of the criteria, sub-criteria and alternatives. With the method it is easier to reach a consensus position, saving the particularities of each expert.

The stable compromise solution achieved with the proposed expert system is a combination of a biological treatment, a chemical oxidation, an ultrafiltration and an activated carbon process, $F^c$ in Figure 2. We can also observe that there is another solution with consensus in positions $2^{nd}$, biological and physical – chemical treatment in combination with reverse osmosis solution. $F^c$ has an acceptable stability in decision making and is the best ranked by the Q value, but it doesn't present an acceptable advantage with respect to the one ranking second in the list by Q. The first proposed treatment is "in closeness" with the second one, in the terms proposed by the method applied. It also is the best ranked by *S* (majority rule) and *R* (minimum individual regret). As it can be observed in Figure 2, the proposed solution is close to the ideal alternative in most of the criteria considered. We can also observe that the second solution is very close to the ideal solution. BCU is preferred in some aspects and BPR in other, with small differences between them, but in odor, it being the heaviest factor in expert's opinion (see Table 9), BCU is preferred. Apart from odor, O&M, quality of the effluent and resulting waste treatment have an important overall weight, as shown in Table 9, reflecting that the economic and environmental criteria are decisive in the choosing of the solution. In addition, lagooning has a complete rejection consensus among the experts consulted in our case. The results obtained indicate that a good decision in the design stage can provide an ideal solution in all cases, with great social acceptance and environmentally friendly. Finally, the proposed expert system has been shown as a reliable technique in decision-making for selecting the optimal system of leachate purification in waste plants.

## Conflict of interest

The authors declare that they have no conflict of interest.

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Figure 1

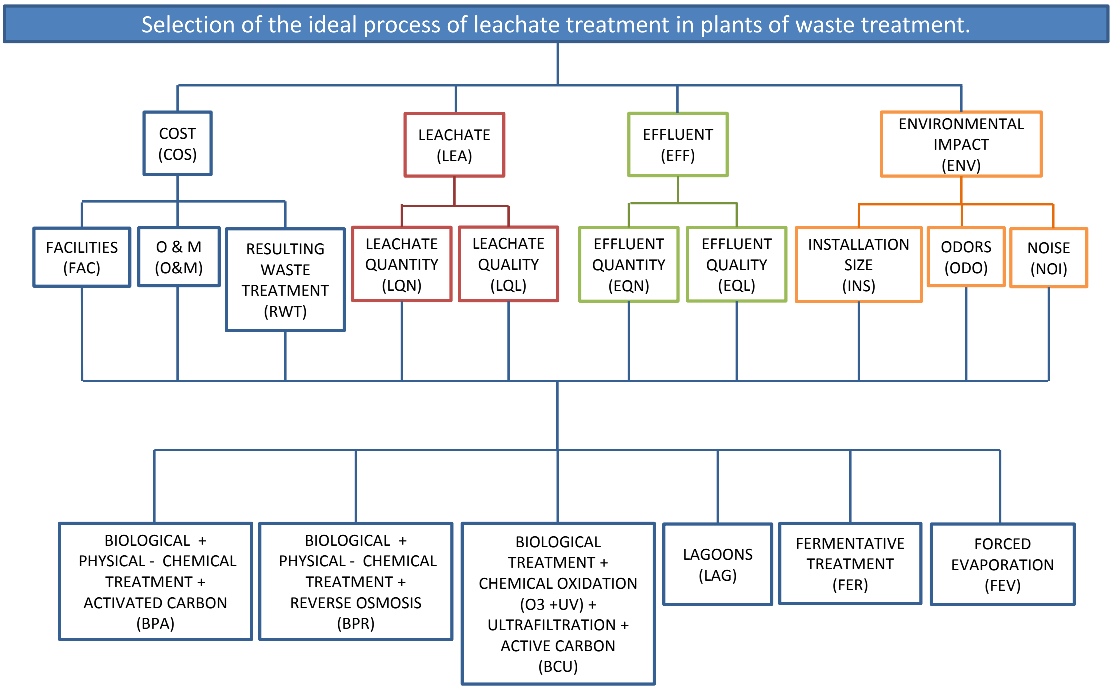


**Fig 1** Hierarchy tree obtained after first questionnaire.

Figure 2

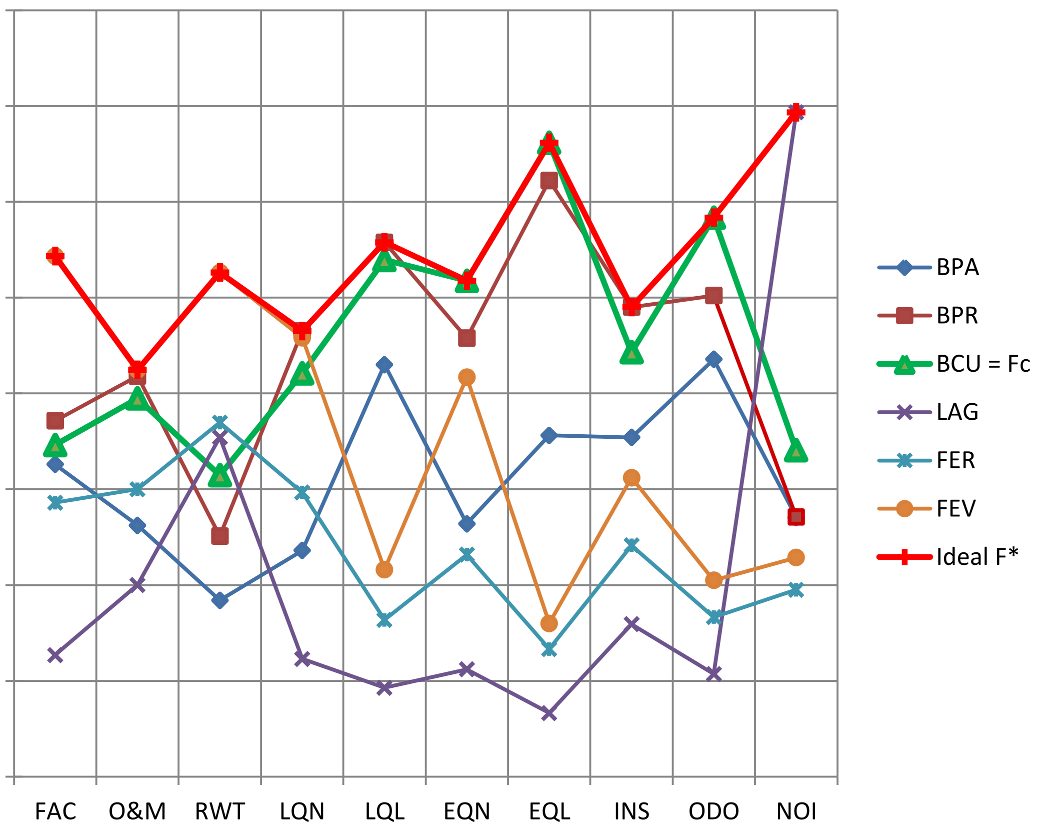


**Fig. 2** Comparison of technical treatments with ideal F* and compromise Fc solutions in VIKOR Method.

Table 1

**Table 1.-** Saaty's Fundamental Scale for Pairwise Comparisons (Saaty 2012).

| Intensity of Importance | Definition | Explanation |
|---|---|---|
| 1 | Equal importance | Two activities contribute equally to the objective |
| 3 | Moderate importance | Experience and judgment slightly favor one activity over another |
| 5 | Strong importance | Experience and judgment strongly favor one activity over another |
| 7 | Very strong or demonstrated | An activity is favored very strongly over another. Its dominance demonstrated in practice |
| 9 | Extreme importance | The evidence favoring one activity over another is of the highest possible order of affirmation |

Table 2

**Table 2.-** Questionnaire for evaluating criteria respect to the overall goal

On the selection of the optimal process of treatment of leachate in plants of waste treatment, how much more important is each factor in comparison to others one?

| | More Important | | | | Equal | Less Important | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| COST (COS) | 9 | 7 | 5 | 3 | 1 | 3 | 5 | 7 | 9 | LEACHATE (LEA) |
| COST (COS) | 9 | 7 | 5 | 3 | 1 | 3 | 5 | 7 | 9 | EFFLUENT (EFF) |
| COST (COS) | 9 | 7 | 5 | 3 | 1 | 3 | 5 | 7 | 9 | ENVIRONMENTAL IMPACT (ENV) |
| LEACHATE (LEA) | 9 | 7 | 5 | 3 | 1 | 3 | 5 | 7 | 9 | EFFLUENT (EFF) |
| LEACHATE (LEA) | 9 | 7 | 5 | 3 | 1 | 3 | 5 | 7 | 9 | ENVIRONMENTAL IMPACT (ENV) |
| EFFLUENT (EFF) | 9 | 7 | 5 | 3 | 1 | 3 | 5 | 7 | 9 | ENVIRONMENTAL IMPACT (ENV) |

Table 3

**Table 3.-** Questionnaire for evaluating sub criteria respect to the overall goal, under the terms of each criterion

On the selection of the optimal process of treatment of leachate in plants of waste treatment, how much more important is each sub criterion in comparison to the others one?

| | More Important | | | | Equal | Less Important | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **EVALUATION SUB-CRITERIA OF COST CRITERION** | | | | | | | | | | |
| FACILITIES (FAC) | 9 | 7 | 5 | 3 | 1 | 3 | 5 | 7 | 9 | O & M COST (O&M) |
| FACILITIES (FAC) | 9 | 7 | 5 | 3 | 1 | 3 | 5 | 7 | 9 | RESULTING WASTE TREATMENT COST (RWT) |
| O & M COST (O&M) | 9 | 7 | 5 | 3 | 1 | 3 | 5 | 7 | 9 | RESULTING WASTE TREATMENT COST (RWT) |
| **EVALUATION SUB-CRITERIA OF LEACHATE CRITERION** | | | | | | | | | | |
| LEACHATE QUANTITY (LQN) | 9 | 7 | 5 | 3 | 1 | 3 | 5 | 7 | 9 | LEACHATE QUALTITY (LQL) |
| **EVALUATION SUB-CRITERIA OF EFFLUENT CRITERION** | | | | | | | | | | |
| EFFLUENT QUANTITY (EQN) | 9 | 7 | 5 | 3 | 1 | 3 | 5 | 7 | 9 | EFFLUENT QUALITY (EQL) |
| **EVALUATION SUB-CRITERIA OF ENVIRONMENTAL CRITERION** | | | | | | | | | | |
| SIZE OF THE INSTALLATION (INS) | 9 | 7 | 5 | 3 | 1 | 3 | 5 | 7 | 9 | ODOR (ODO) |
| SIZE OF THE INSTALLATION (INS) | 9 | 7 | 5 | 3 | 1 | 3 | 5 | 7 | 9 | NOISE (NOI) |
| ODOR (ODO) | 9 | 7 | 5 | 3 | 1 | 3 | 5 | 7 | 9 | NOISE (NOI) |

Table 4

**Table 4.-** Evaluation results of the criteria with respect to overall goal.
Results for every expert (E1 to E11)

| Pairwise Criteria | | | E1 | E2 | E3 | E4 | E5 | E6 | E7 | E8 | E9 | E10 | E11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COS | vs | LEA | 5 | 9 | 7 | 9 | 3 | 1/3 | 1/7 | 3 | 1/3 | 5 | 1/3 |
| COS | vs | EFF | 1/3 | 5 | 1/3 | 3 | 1/7 | 5 | 1/5 | 1 | 1/5 | 3 | 1/3 |
| COS | vs | ENV | 3 | 7 | 3 | 7 | 1/3 | 3 | 1/7 | 3 | 1 | 7 | 1/7 |
| LEA | vs | EFF | 1/7 | 1/5 | 1/9 | 1/7 | 1/9 | 7 | 1 | 1 | 1/3 | 1/3 | 1 |
| LEA | vs | ENV | 1/3 | 1/3 | 1/5 | 1/3 | 1/5 | 5 | 3 | 5 | 5 | 3 | 1 |
| EFF | vs | ENV | 7 | 5 | 5 | 7 | 5 | 1/3 | 3 | 5 | 5 | 5 | 1 |

Table 5

**Table 5.-** Evaluation results of the sub criteria with respect to each criterion. Results for every expert (E1 to E11)

| Crit. | Pairwise Sub criteria | | | E1 | E2 | E3 | E4 | E5 | E6 | E7 | E8 | E9 | E10 | E11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COS | FAC | vs | O&M | 1/9 | 1/9 | 1/7 | 1/9 | 3 | 1/3 | 1/5 | 1/5 | 1/5 | 1/3 | 1 |
| | FAC | vs | RWT | 1/5 | 1/5 | 1/5 | 1/3 | 1/5 | 1/7 | 1/5 | 1/3 | 1/3 | 1 | 1 |
| | O&M | vs | RWT | 3 | 5 | 3 | 7 | 1/7 | 1/5 | 1 | 3 | 3 | 3 | 1/3 |
| LEA | LQN | vs | LQL | 1/7 | 1/3 | 1/9 | 1/7 | 7 | 5 | 1/5 | 1/3 | 1 | 3 | 1 |
| EFF | EQN | vs | EQL | 1/7 | 1/3 | 1/5 | 3 | 1/5 | 5 | 1/5 | 1/3 | 1/7 | 1/3 | 1/5 |
| ENV | INS | vs | ODO | 1/3 | 1/3 | 1/3 | 1/5 | 3 | 3 | 1/7 | 1 | 1/3 | 3 | 1 |
| | INS | vs | NOI | 5 | 5 | 3 | 3 | 9 | 3 | 1/5 | 5 | 1 | 9 | 1 |
| | ODO | vs | NOI | 7 | 7 | 5 | 7 | 7 | 1/7 | 5 | 9 | 5 | 5 | 1 |

Table 6

**Table 6.-** Average random consistency (RCI) (Saaty 2012).

| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| RCI | 0 | 0 | 0.52 | 0.89 | 1.11 | 1.25 | 1.35 | 1.40 | 1.45 | 1.49 |

Table 7

**Table 7.-** Pairwise matrix for sub criterion FAC and its eigenvector

| | BPA | BPR | BCU | LAG | FER | FEV | EIGENVECTOR |
|---|---|---|---|---|---|---|---|
| BPA | 1.0000 | 0.8639 | 0.8639 | 2.9344 | 1.3179 | 0.5125 | 0.1630 |
| BPR | 1.1576 | 1.0000 | 1.4135 | 2.9140 | 1.2297 | 0.5327 | 0.1857 |
| BCU | 1.1576 | 0.7075 | 1.0000 | 3.1694 | 1.1306 | 0.7075 | 0.1731 |
| LAG | 0.3408 | 0.3432 | 0.3155 | 1.0000 | 0.4494 | 0.3035 | 0.0634 |
| FER | 0.7588 | 0.8132 | 0.8845 | 2.2250 | 1.0000 | 0.5659 | 0.1430 |
| FEV | 1.9514 | 1.8773 | 1.4135 | 3.2944 | 1.7672 | 1.0000 | 0.2717 |

$\lambda_{max} = 6.0543$, CI = 0.0109, CR = 0.0087<0.1 OK

**Table 8.-** Technical treatments matrix

| | FAC | O&M | RWT | LQN | LQL | EQN | EQL | INS | ODO | NOI |
|---|---|---|---|---|---|---|---|---|---|---|
| BPA | 0.1630 | 0.1312 | 0.0920 | 0.1180 | 0.2150 | 0.1320 | 0.1781 | 0.1771 | 0.2178 | 0.1353 |
| BPR | 0.1857 | 0.2090 | 0.1256 | 0.2326 | 0.2789 | 0.2288 | 0.3111 | 0.2450 | 0.2511 | 0.1356 |
| BCU | 0.1731 | 0.1975 | 0.1573 | 0.2105 | 0.2697 | 0.2588 | 0.3308 | 0.2215 | 0.2918 | 0.1705 |
| LAG | 0.0634 | 0.1001 | 0.1771 | 0.0615 | 0.0464 | 0.0560 | 0.0332 | 0.0796 | 0.0536 | 0.3467 |
| FER | 0.1430 | 0.1500 | 0.1848 | 0.1483 | 0.0819 | 0.1159 | 0.0667 | 0.1207 | 0.0833 | 0.0975 |
| FEV | 0.2717 | 0.2123 | 0.2631 | 0.2291 | 0.1081 | 0.2084 | 0.0800 | 0.1561 | 0.1025 | 0.1144 |

Table 9

**Table 9.-** Sub criteria vector

| FAC | O&M | RWT | LQN | LQL | EQN | EQL | INS | ODO | NOI |
|---|---|---|---|---|---|---|---|---|---|
| 0.0341 | 0.1399 | 0.1034 | 0.0601 | 0.0968 | 0.0424 | 0.1145 | 0.0970 | 0.1432 | 0.0372 |

Table 10

**Table 10.-** f* and f- values for all technical treatments.

| | FAC | O&M | RWT | LQN | LQL | EQN | EQL | INS | ODO | NOI |
|---|---|---|---|---|---|---|---|---|---|---|
| f* | 0.2717 | 0.2123 | 0.2631 | 0.2326 | 0.2789 | 0.2588 | 0.3308 | 0.2450 | 0.2918 | 0.3467 |
| f- | 0.0634 | 0.1001 | 0.0920 | 0.0615 | 0.0464 | 0.0560 | 0.0332 | 0.0796 | 0.0536 | 0.0975 |

**Table 11.-** $S_i$, $R_i$ and $Q_i$ values for all technical treatments.

| | Wc | BPA | BPR | BCU | LAG | FER | FEV |
|---|---|---|---|---|---|---|---|
| FAC | 0.0341 | 0.0178 | 0.0141 | 0.0161 | 0.0341 | 0.0211 | 0.0000 |
| O&M | 0.1399 | 0.1012 | 0.0041 | 0.0185 | 0.1399 | 0.0776 | 0.0000 |
| RWT | 0.1034 | 0.1034 | 0.0831 | 0.0640 | 0.0520 | 0.0473 | 0.0000 |
| LQN | 0.0601 | 0.0403 | 0.0000 | 0.0078 | 0.0601 | 0.0296 | 0.0012 |
| LQL | 0.0968 | 0.0266 | 0.0000 | 0.0038 | 0.0968 | 0.0820 | 0.0711 |
| EQN | 0.0424 | 0.0265 | 0.0063 | 0.0000 | 0.0424 | 0.0299 | 0.0105 |
| EQL | 0.1145 | 0.0587 | 0.0076 | 0.0000 | 0.1145 | 0.1016 | 0.0965 |
| INS | 0.0970 | 0.0399 | 0.0000 | 0.0138 | 0.0970 | 0.0729 | 0.0522 |
| ODO | 0.1432 | 0.0445 | 0.0245 | 0.0000 | 0.1432 | 0.1254 | 0.1139 |
| NOI | 0.0372 | 0.0315 | 0.0315 | 0.0263 | 0.0000 | 0.0372 | 0.0347 |
| | Si | 0.4904 | 0.1711 | 0.1502 | 0.7800 | 0.6247 | 0.3801 |
| | Ri | 0.1034 | 0.0831 | 0.0640 | 0.1432 | 0.1254 | 0.1139 |
| | Qi | 0.5190 | 0.1375 | 0.0000 | 1.0000 | 0.7643 | 0.4971 |

Table 12

**Table 12.-** Best S*and R*, and worst $S^-$and $R^-$ for all technical treatments.

| | | | |
|---|---|---|---|
| S* | 0.1502 | S- | 0.7800 |
| R* | 0.0640 | R- | 0.1432 |

**Table 13.-** Leachate treatments ranking.

| Technical treatments | BPA | BPR | BCU | LAG | FER | FEV |
|---|---|---|---|---|---|---|
| Si | 4 | 2 | 1 | 6 | 5 | 3 |
| Ri | 3 | 2 | 1 | 6 | 5 | 4 |
| Qi | 4 | 2 | 1 | 6 | 5 | 3 |

| Position | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Si | BCU | BPR | FEV | BPA | FER | LAG |
| Ri | BCU | BPR | BPA | FEV | FER | LAG |
| Qi | BCU | BPR | FEV | BPA | FER | LAG |