

The application of the analytic network process to the assessment of best available techniques

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ABSTRACT

The European Integrated Pollution Prevention and Control Bureau produces reference documents on Best Available Techniques, called BREFs. These documents give technical and descriptive information about the installations that represent a significant pollution potential in Europe. However, they do not provide an assessment of the Best Available Techniques, which is a decision to be made by the competent environmental authority. The present work proposes a decision-making process for assessing Best Available Techniques based on the Analytic Network Process. Seven evaluation criteria, grouped into three clusters, have been proposed. The process is applied to a case study and the results are described and analyzed. As a main conclusion, this paper describes a robust and scientific method for a better implementation of the Integrated Pollution Prevention and Control approach.

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1. Introduction

The real cause of the current financial crisis is the crisis of the industrial model based on intensive mass production and extensive use of cheap resources. This model, which was highly successful in the twentieth century, came to its end in the last decade. Today, eco-efficient innovation or eco-innovation has become a key concept in the EU (Jänicke, 2010).

One of the three priorities of the Europe 2020 Strategy (European Commission, 2010) is sustainable growth through the promotion of an economy that is greener, more competitive and more efficient in its use of resources. But to reach this goal substantial changes in the regulations are needed (Ashford and Hall, 2011).

One of the most powerful tools for the promotion of eco-innovations is Directive 2008/1/EC concerning integrated pollution prevention and control (European Parliament, 2008), known as the Integrated Pollution Prevention and Control (IPPC) Directive. This Directive will be repealed on 7 January 2014 by Directive 2010/75/UE (European Parliament, 2010) on industrial emissions.

The IPPC Directive establishes a procedure for authorizing the activities listed in Annex 1 so that the owner of a new facility must

request permission from the competent authority, which is then required to conduct an environmental assessment of the activity (EA-IPPC). The EA-IPPC takes into consideration all factors involved in the activity: characteristics of the installation, industrial processes, impact of pollutants on water, soil, air and workers health. The results of the EA-IPPC serve to write a report specifying the operational requirements of the activity. This report is called the Integrated Environmental Authorization (IEA) and should comply with the IPPC regulations. The IPPC approach considers the establishment of emission limit values based on Best Available Techniques (BAT) but it does not prescribe the use of any technique or specific technology, or take into account the technical characteristics of the installation concerned, its geographical location and local environmental conditions.

According to the IPPC Directive, BAT means the most effective and advanced stage in the development of activities and their methods of operation which indicates the practical suitability of particular techniques for providing in principle the basis for emission limit values designed to prevent and, where that is not practicable, generally to reduce emissions and the impact on the environment as a whole.

For the correct implementation of the IPPC approach the competent authority should know and assess all existing BAT before conducting the IEA of an IPPC installation. Similarly, the holder of the facility should include the most suitable BAT in his application form. However, the use of BAT is not restricted to the scope of the

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IPPC Directive, but any company can implement a BAT in its production process as a tool to improve eco-efficiency and consequently competitiveness. This is because the IPPC approach prioritizes pollution prevention over treatment (Honkasalo et al., 2005).

The European Commission, through the European IPPC Bureau, publishes reference documents for different IPPC sectors (mainly industrial and farming) that contain a description of the main processes, environmental aspects and associated list of BAT. These documents, called Reference Documents on Best Available Techniques (BREF) are publicly available and provide technical details and general descriptive information, but do not include an assessment of these techniques, which is a key issue for the correct implementation of the IPPC approach.

The implementation of BAT generally involves the installation of new equipment or machinery. The correct selection of a BAT is an important decision for a company, especially if it is located in an environmentally sensitive area (Samarakoon and Gudmestad, 2011). Using the right equipment can improve the production process, facilitate the efficient use of labor, increase productivity and improve flexibility. The selection of new equipment can become a long and difficult process, requiring sound knowledge and extended experience. For proper and effective evaluation of the alternatives, decision makers have to analyze a large amount of data and consider various quantitative and qualitative criteria. In other words, it is a multi-criteria decision-making (MCDM) problem (Ayag and Ozdemir, 2006).

The Life Cycle Assessment (LCA) approach seems to be the most environmentally suitable technique to compare different types of equipment because it determines the environmental impacts associated with resource use and pollutant discharges to the environment. LCA application is regulated by ISO 14040:2006, though it is difficult to find accurate data on the characteristics and potential impacts of the machinery under evaluation. This is another important pitfall hindering the correct implementation of the IPPC Directive (Bréchet and Tulkens, 2009).

A different approach for the evaluation of BAT is based on Multi-Criteria Decision Analysis (MCDA). Belton and Stewart (2002) define MCDA as a term that includes a set of concepts, methods and techniques that seek to help individuals or groups to make decisions, which involve several points of view in conflict and multiple stakeholders. All these MCDA concepts and methods have been largely studied in the Operational Research literature (Belton and Stewart, 2002; Pomerol and Barba-Romero, 2000; Figueira et al., 2005).

In this work the Analytic Network Process (ANP) proposed by Saaty (2001) as a generalization of the Analytic Hierarchy Process (AHP) (Saaty, 1980) is used to evaluate BAT. The process starts with the formulation of the problem and ends with a comparison of the results obtained from both techniques.

MCDA techniques have been used for technology assessment: Doukas et al. (2006) used PROMETHEE II to assess technologies for power generation, Bollinger and Pictet (2008) used ELECTRE III to evaluate waste incineration technologies, Gómez-López et al. (2009) used TOPSIS to assess disinfection technologies for wastewater reuse.

However, there are few studies that apply MCDA techniques to the evaluation of BAT. Dijkmans (2000) selected BAT for two IPPC activities through qualitative assessment based on BAT availability in the market, environmental impacts and economic feasibility. Schultmann et al. (2001) compared different BAT from an economic viewpoint by estimating the costs associated with initial investment and maintenance. Geldermann and Rentz (2001) used PROMETHEE for the evaluation of BAT that can reduce atmospheric emissions, especially when using uncertain data. These authors proposed the reference installation approach in 2004, which consists of assigning a class type to the IPPC installation under evaluation, so that the

same emission measures (BAT) are applied to all facilities belonging to the same IPPC category. In their work the authors also used AHP (Geldermann and Rentz, 2004). Georgopoulou et al. (2008) developed a software tool for BAT assessment called BAT Economic Attractiveness Tool. The tool performs a quantitative analysis of the economic and environmental effects resulting from the implementation of a BAT. Barros et al. (2009) identified and analyzed the potential BAT for a fish farm from different published BREF and their experience in the sector in Galicia, and selected those BAT that could improve environmental performance. Liu and Wen (2012) selected BAT using Data Envelopment Analysis, for the case of thermal power plants in China.

2. Overview of AHP/ANP

The Analytic Hierarchy Process (AHP) and the Analytic Network Process (ANP) are two methods proposed by Saaty (1980, 1996a, 2001, 2005, 2008). AHP is a well-known technique based on the fact that the inherent complexity of a multiple criteria decision-making problem can be modeled breaking down it into several levels in such a way that they form a hierarchy with unidirectional hierarchical relationships between levels. The top level of the hierarchy is the main goal of the decision problem. The lower levels are the tangible and/or intangible criteria and subcriteria that contribute to the goal. The bottom level is formed by the alternatives to evaluate in terms of the criteria. In each hierarchical level paired comparisons are made with judgments using numerical values taken from the AHP absolute fundamental scale of 1–9. These comparisons lead to dominance matrices from which ratio scales are derived in the form of principal eigenvectors. These matrices are positive and reciprocal ($a_{ij} = 1/a_{ji}$). The synthesis of AHP combines multidimensional scales of measurement into a single one-dimensional scale of priorities. The method also calculates a consistency ratio (CR) to verify the coherence of the judgments, which must be about 0.10 or less to be acceptable. Mathematical foundations of AHP can be found in Saaty (1994, 1996b).

AHP is conceptually easy to use; however its strict hierarchical structure cannot address the complexities of many real-world problems. As a solution, Saaty proposed the ANP model, a generalization of AHP. ANP represents a decision-making problem as a network of criteria and alternatives (all called elements), grouped into clusters. All the elements in the network can be related in any possible way, i.e. a network can incorporate feedback and complex inter-relationships within and between clusters. This provides a more accurate modeling of complex settings. The influence of the elements in the network on other elements in that network can be represented with a supermatrix. This new concept consists of a two-dimensional element-by-element matrix which adjusts the relative importance weights in individual pairwise comparison matrices to build a new overall supermatrix with the eigenvectors of the adjusted relative importance weights. According to Saaty (2001), the ANP model comprises the following steps:

- (i) Identifying the components and elements of the network and their relationships.
- (ii) Conducting pairwise comparisons on the elements.
- (iii) Placing the resulting relative importance weights (eigenvectors) in pairwise comparison matrices within the supermatrix (unweighted supermatrix).
- (iv) Conducting pairwise comparisons on the clusters.
- (v) Weighting the blocks of the unweighted supermatrix, by the corresponding priorities of the clusters, so that it can be column-stochastic (weighted supermatrix).
- (vi) Raising the weighted supermatrix to limiting powers until the weights converge and remain stable (limit supermatrix).

Other authors have used the AHP method for the assessment of different technologies. Tabucanon et al. (1994) used AHP for the selection of machines in flexible manufacturing systems. Prabhu and Vizayakumar (1996) used AHP to select technologies through technical, socio-economic and environmental criteria. Chan et al. (2001), Cziner et al. (2005) and Gerdşri and Kocaoglu (2007) used AHP to integrate new industrial equipment in the production process by various criteria: economic costs, technological efficiency, safety, environmental factors, and so on. Chowdhury and Husain (2006) used AHP in combination with the fuzzy set theory for evaluation of drinking water treatment technology. Remanufacturing of technologies has been assessed using AHP in recent studies (Subramoniam et al., in press; Du et al., 2012; Jiang et al., 2011).

ANP has also been used in environmental works. For example, Erdoğan et al. (2006) used ANP to select the optimal type of fuel for residential heating in Turkey, Ulutas (2005) and Dağdeviren and Eraslan (2008) used ANP to prioritize energy policies in Turkey, Köne and Büke (2007) used ANP to evaluate fuels for electricity generation, Aragonés-Beltrán et al. (2010a) to locate municipal solid waste treatment plants, Gómez-Navarro et al. (2009) to propose an index of environmental pressure for urban development planning, Yüksel and Dağdeviren (2007) to select technologies in a textile industry. However, no ANP applications were found in the literature that evaluate BAT.

The reasons for using an ANP-based decision analysis approach in the present work are: (i) the assessment of BAT is a multi-criteria decision problem; (ii) there are dependencies among groups of criteria and between these and the alternative techniques under evaluation; (iii) the detailed analysis of the inter-relationships between clusters forces the decision makers to carefully reflect on their project priority approach and on the decision-making

problem itself and helps DMs to gain a better understanding of the problem and to make a more reliable final decision, (iv) the model permits the consideration of qualitative and quantitative criteria, (v) the model also takes into consideration the opinions of a multidisciplinary team.

Its main drawback is the difficulty in modeling influences among the elements involved in the evaluation process. In complex models the questionnaires generally contain simple questions but there are too many, which may cause tiredness and boredom in the decision maker. Subnets and BOCR analysis (Benefits, Opportunities, Costs and Risks) can be used instead.

Another problem may arise when the number of alternatives to be assessed is very high (more than 7) or they are heterogeneous. In this case, Saaty suggests applying ratings evaluation or grouping alternatives into homogeneous groups (Saaty and Shang, 2011).

3. The BAT assessment process and the ANP modeling approach

The BAT assessment method proposed in this work is shown in Fig. 1. The experts of the competent authority act as Decision Maker (DM) as specified in the IPPC Directive. These experts are a multi-disciplinary team consisting of lawyers, engineers, biologists, chemists and environmental technicians, who are specialized in different areas related to industrial activity and its impact on the environment.

3.1. Phase of problem analysis

The starting point for the selection of a BAT is the BREF documents, as well as the national guidelines and, occasionally, local

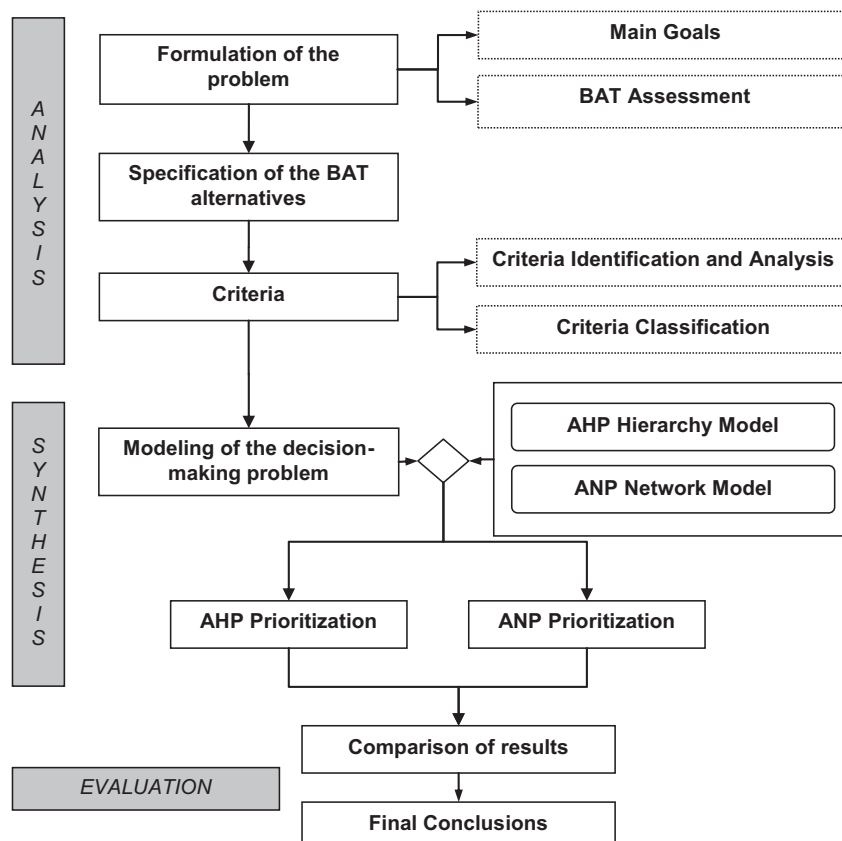


Fig. 1. BAT assessment model (adapted from Aragonés-Beltrán et al., 2010b).

guidelines. These documents are prepared and updated by multi-disciplinary working groups, composed of personnel from the competent authorities, representatives of the productive sector, technology centers, professional associations and environmentalists. From a methodological point of view, these working groups are considered as a decision group with different views, so that these documents do not contain a BAT assessment.

BREF design is an iterative process that involves the following steps:

- Identification of the key environmental aspects of the productive sector.
- Analysis of the BAT techniques that act on these key issues, including costs, resource use and associated environmental impacts.
- Identification of best environmental performance, according to information available in the European Union and worldwide.
- Selection of a BAT in accordance with Annex IV of the IPPC Directive, including a description of its environmental advantages

The BREFs reflect the overall environmental situation of a given industrial sector but cannot analyze each individual facility (Schoenberger, 2009). Therefore, these documents only include a list of BATs for each stage of the production process.

The formulation of the problem under analysis in this paper is: “Given a particular facility for which the holder requests the IEA, the competent authority should evaluate the BAT for each environmental aspect in the available BREF documents before issuing the corresponding authorization.”

The alternatives to evaluate will be selected by the DM based on the BREFs and his professional experience. These are the considerations to be taken into account generally or in specific cases when determining best available techniques, as defined in Annex IV of the IPPC Directive:

- the use of low-waste technology;
- the use of less hazardous substances;
- the furthering of recovery and recycling of substances generated and used in the process and of waste, where appropriate;
- comparable processes, facilities or methods of operation which have been tried with success on an industrial scale;
- technological advances and changes in scientific knowledge and understanding;
- the nature, effects and volume of the emissions concerned;
- the commissioning dates for new or existing installations;
- the length of time needed to introduce the best available technique;
- the consumption and nature of raw materials (including water) used in the process and energy efficiency;

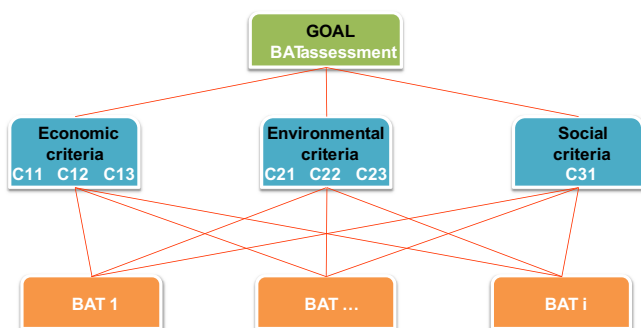


Fig. 2. AHP-based hierarchy model for BAT assessment.

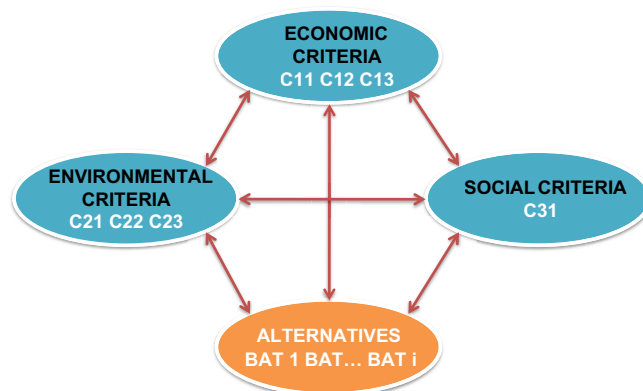


Fig. 3. ANP-based network model for BAT assessment.

- the need to prevent or reduce to a minimum the overall impact of the emissions on the environment and the risks to it;
- the need to prevent accidents and to minimize the consequences for the environment;
- the information published by the Commission pursuant to Article 17(2), second subparagraph, or by international organizations.

Based on these criteria and the scientific literature, this paper proposes seven evaluation criteria, grouped into three clusters:

Cluster 1: Economic Criteria.

- C11 Implementation costs: they are basically the costs of implementation of BAT, i.e. the investment and engineering costs as well as the implementation costs (Cziner et al., 2005).
- C12 Resource Consumption: these criteria refer to the operation and maintenance of BAT, the inputs needed for daily operation (water, electricity, raw materials, reagents, etc.) (Barros et al., 2009).
- C13 Energy efficiency: these criteria take into account the BAT power efficiency, which in turn affects productivity (Honkasalo et al., 2005).

Cluster 2: Environmental Criteria.

- C21 Wastewater management: they refer to the quantity and quality of generated wastewater, and its management (Geldermann and Rentz, 2004).
- C22 Air Emissions Management: criteria related to the nature and quantity of air emissions, and their impact on the environment (Georgopoulou et al., 2008).
- C23 Waste management: aspects associated with the amount and type of waste generated and its management according to the waste management hierarchy (Dijkmans, 2000).

Cluster 3: Social criteria (Gómez-López et al., 2009).

Table 1

Local and global weights of the criteria.

Goal	Cluster	Criteria	Local	Global
BAT assessment	Economic criteria 0.741	C11. Implementation costs	0.193	0.143
		C12. Resource consumption	0.268	0.199
		C13. Energy efficiency	0.540	0.400
	Environmental criteria 0.184	C21. Wastewater management	0.319	0.059
		C22. Air emissions management	0.391	0.072
		C23. Waste management	0.291	0.054
	Social criteria 0.074	C31. Workers health	1	0.074

Table 4

Example of the questionnaire about prioritization of elements.

Compare the following elements in the cluster **Environmental criteria** according to their influence upon **C11 Implementation costs** in the cluster **Economic criteria**

A: C21 Wastewater Management

B: C22 Air Emission management

Which has the greatest influence?	<input type="checkbox"/> A	<input checked="" type="checkbox"/> B	<input type="checkbox"/> Equally important	
To what extent?	<input checked="" type="checkbox"/> Moderate	<input type="checkbox"/> Strong	<input type="checkbox"/> Very strong	<input type="checkbox"/> Extreme

to what extent according to Saaty's 1–9 scale? Next, another questionnaire was designed to evaluate the different alternatives based on their relative criteria levels using questions such as: Given a certain criterion and two alternatives to compare, which alternative better satisfies the criterion and to what extent according to Saaty's 1–9 scale? In all individual judgment matrices it was verified that their consistency ratios were less than 0.1

Table 1 shows the local and global (aggregated) weights of the criteria, according to the hierarchy approach.

The criteria rated highest by the DM were energy efficiency (C13) and resource consumption (C12).

Then each member of the DM was asked to assess the BAT for each criterion. When setting individual preferences by means of pairwise comparisons between BAT, it was taken into account that the highest rated BAT were those involving less consumption of resources, lower economic cost, less impact on water, air and workers health, and greater energy efficiency and better waste management. Table 2 shows the scores obtained and the final priority, calculated according to AHP. The higher the score the better the alternative.

The DM's suggestion was to implement BAT 3, use of pneumatic conveying systems.

4.2.2. Network model

4.2.2.1. Determination of the network. This step requires the DM to have a good understanding of the problem using the advice given by the AT based on the data gathered in previous stages. The steps needed for the construction of the network are: i) determination of the elements, ii) determination of the clusters, and iii) determination of the influence network. The first two steps of identification and clustering of criteria have been described in the section Problem Analysis.

For the determination of the influences between the elements of the network a zero–one interfactorial dominance matrix was used (Saaty, 2001) whose elements a_{ij} take the value 1 or 0 depending on whether there is or there is not some influence of element i on element j . The rows and columns of the matrix are formed by all the elements of the network.

In ANP, the numerical data can be represented graphically and thus show the influence pattern of the network. This step is essential for further development of the process because if all the complexity of the real-world case study is to be transferred to the model, the DM has to accurately identify the influences of some

elements upon others based on his knowledge and experience. If the DM fails to identify one influence, the model will not take it into account and some valuable information will be lost (Aragónés-Beltrán et al., 2010a). For this reason the DM was asked to identify these influences, which are shown in Table 3.

The DM made the following assumptions for the case study under analysis: i) there are no influences among the different BAT due to the fast advance of environmental technology. This implies the assumption that the BAT will always be different and independent and, therefore, there will be no influence on each other; ii) there are no influences among criteria of the same cluster. In the case of environmental criteria (C21, C22 and C23), certain contaminant transfer may occur between the 3 vectors corresponding to these criteria (water, air and soil). However, in this case the DM saw no influence among these criteria, iii) there is no influence among the three economic criteria (C11, C12 and C13).

4.2.2.2. Determination of element and cluster priorities. The next stage includes all the steps of the ANP model. The first step consists of assigning priorities to related elements in order to build the unweighted supermatrix. To this end, each element (criterion or alternative) is analyzed in terms of which of the other elements, which have influence on it and belong to a certain cluster, exerts a greater influence on it and to what extent. In this way, for each column of the unweighted supermatrix we can identify blocks corresponding to each of the clusters whose values form the eigenvector that represents the relative influence of the elements of each cluster on the element under consideration. Each eigenvector has been calculated from the corresponding pairwise comparison matrices.

Due to the fact that in the case study different elements from different clusters have influences on one element the unweighted matrix is non-stochastic by columns. Thus according to Saaty (2001), all clusters that exert any kind of influence upon each group have to be prioritized using the corresponding cluster pairwise comparison matrices. The value corresponding to the priority associated with a certain cluster weights the priorities of the elements of the cluster on which it acts (in the unweighted supermatrix), and the weighted supermatrix can be generated. Appendix B shows the unweighted and weighted supermatrices.

To this end, a questionnaire was designed as a multiple-choice test and organized into tables that grouped the questions relative to the pairwise comparison matrices. The consistency ratios of the

Table 5

Example of the questionnaire about prioritization of clusters.

Compare the following groups that have some influence upon the cluster **Environmental criteria**

A: Alternatives

B: Economic criteria

Which has the greatest influence?	<input checked="" type="checkbox"/> A	<input type="checkbox"/> B	<input type="checkbox"/> Equally important	
To what extent?	<input checked="" type="checkbox"/> Moderate	<input type="checkbox"/> Strong	<input type="checkbox"/> Very strong	<input type="checkbox"/> Extreme

Table 6
BAT priorities according to the network approach.

	Priority
BAT 1	0.435
BAT 2	0.119
BAT 3	0.446

Table 7
BAT priorities depending on the decision model used.

	AHP	Ranking	ANP
BAT 3	0.458	1	0.446
BAT 1	0.430	2	0.435
BAT 2	0.112	3	0.119

judgment matrices were always lower than 0.1. Tables 4 and 5 show an example of the questionnaire.

4.2.2.3. Calculation of the limit matrix and resulting prioritization. By raising the weighted supermatrix to successive powers the limit matrix is obtained. The results of the model are shown in Table 6, expressed as distributive mode.

BAT 3 (use of pneumatic conveying systems) is the most appropriate BAT to reduce particulate emissions to the atmosphere in the installation of this case study with a priority of 44.6%. On the other hand, the priority of BAT 1 (covering of the conveyor working with dusty materials) is 43.5%, similar to that of BAT3.

4.3. Phase of evaluation of results

Table 7 shows the results obtained with each decision model. In this case study, there are not noticeable differences between BAT prioritization in both decision analysis models, being BAT 3 slightly better than BAT 1.

If the criteria weights obtained in the hierarchy model are compared to the criteria influences obtained in the network model some differences can be observed (Table 8).

In the hierarchy model the most important criteria are the economic criteria, while in the ANP model criterion C22 (Air Emissions Management) gains substantial influence. This is logical because they are evaluating BAT for the reduction of particulate emissions to the atmosphere. According to the DM, these results seem more logical than those initially obtained with the hierarchy model.

Table 9 shows the weights/influences of the higher-level criteria (clusters). One can see that in the AHP model the DM gives great importance to the economic criteria, while in the network model this cluster loses influence in favor of the other two clusters. This is in agreement with the principles of sustainable development, whereby the three clusters should tend to have a similar importance.

Table 10 shows a comparison of the number of individual judgments in the hierarchy and network models. It also indicates

Table 9
Comparison of the priorities of the clusters depending on the decision model used.

Clusters	AHP	ANP	Clusters
Economic criteria	0.741	0.565	Economic criteria
Environmental criteria	0.184	0.307	Environmental criteria
Social criteria	0.074	0.128	Social criteria

Table 10
Number and type of individual judgments for the evaluation of three BAT in AHP and ANP.

	AHP	ANP
Comparison of clusters	3 comparisons	$3 \times 4 = 12$ comparisons
Comparison of evaluation criteria	$2 \times 3 = 6$ comparisons	$3 \times 8 = 24$ comparisons
Comparison of BAT with respect to evaluation criteria	$3 \times 7 = 21$ comparisons	$3 \times 7 = 21$ comparisons
Comparison of evaluation criteria with respect to BAT	–	$3 \times 6 = 18$ comparisons

which judgments should include IPPC considerations. The conclusions drawn from the table are:

- For an assessment of three BAT with seven evaluation criteria, each member of the DM has to give 45 judgments (pairwise comparisons) more in the ANP model than in the AHP model (75 versus 30 comparisons). Consequently ANP requires greater efforts from the DM.
- The implementation of the IPPC approach is more effective in the evaluation of BAT by ANP, as the analysis of BAT influences on the criteria is only possible using this method.

4.4. Sensitivity analysis

Judgments in any decision-making problem are surrounded by imprecision, so that results can be modified. It is therefore useful to perform a sensitivity analysis to analyze how the results are influenced by possible changes in some elements of the decision problem.

In the hierarchical model, this analysis is relatively simple to do. The weights on each of the criteria can be changed within a range of variation, by keeping the weight proportion of the others and observing the results. The influences of some alternatives over certain criteria can also be changed, if it is thought there may be imprecision in these assessments.

Fig. 4 shows the change produced in the AHP alternative priorities when the weight of the criterion C13 Energy efficiency is

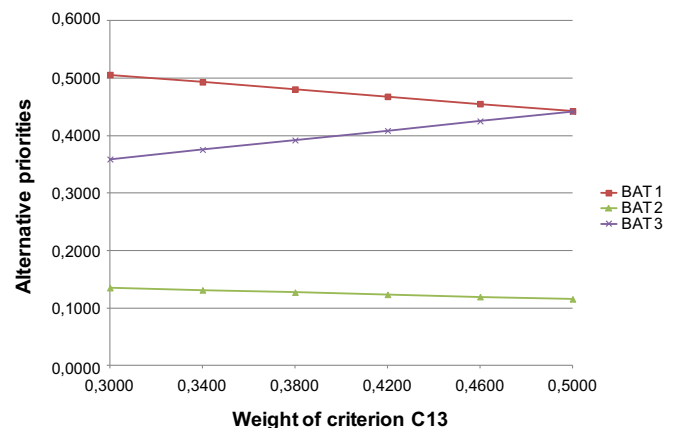


Fig. 4. Sensitivity analysis hierarchy model. Criterion C13.

Table 8
Comparison of the priorities of the criteria depending on the decision model used.

Criteria	AHP	ANP	Criteria
C13. Energy efficiency	0.400	0.223	C11. Implementation costs
C12. Resource consumption	0.199	0.209	C13. Energy efficiency
C11. Implementation costs	0.143	0.148	C22. Air emissions management
C31. Workers health	0.074	0.133	C12. Resource consumption
C22. Air emissions management	0.072	0.128	C31. Workers health
C21. Wastewater management	0.059	0.086	C21. Wastewater management
C23. Waste management	0.054	0.072	C23. Waste management

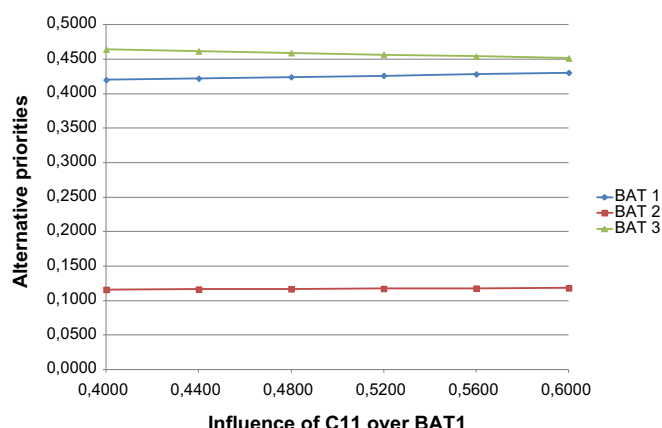


Fig. 5. Sensitivity analysis network model. Influence of Criterion C11 over BAT1.

modified within a range of $\pm 25\%$. We can observe that, when the weight of this criterion is increased in 25% (from 0.4 to 0.5), the alternative BAT3 reaches the same priority as BAT1. The same process has been made for the rest of criteria and no significant changes have been observed.

In the network model, the analysis is more complex to perform. Possible solutions are: to consider those values of the weighted matrix that arose in the discussion between the DM team members; discuss possible changes to certain values in the array of clusters, or remove certain influences among elements in the model. To illustrate this analysis, Fig. 5 shows the evolution of ANP alternative priorities when the influence of Criterion C11 Implementation Costs over BAT1 is modified within a range of 20%.

5. Conclusions

This paper presents a new approach for the evaluation of BAT based on two multi-criteria decision models, AHP and ANP. The selection of the best BAT to improve environmental impact of an industry is a decision to be made by the competent environmental authority, who must evaluate different BAT included in the reference documents. The IPPC Directive does not specify any assessment method. This paper describes a robust and scientific method for a better implementation of the IPPC approach.

The method has been applied to a case study of an Integrated Environmental Authorization granted to a ceramic industry of Castellón (Spain), which sets the limit value for particulate emissions to the atmosphere. The hierarchy model and the network model were used in the analysis. AHP was easier to use and understand by the DM. However, given that the assessment of BAT depends on the characteristics of the BAT and the IPPC installation and its environmental conditions, it becomes evident that there is some kind of influence among the different elements of the decision problem. Consequently, whenever possible, it is preferable to use the network model.

The analysis of the results obtained allowed the DM to observe which criteria that initially were considered as very significant in the hierarchy model, in the network model did not exert such a great influence. This is because in the hierarchical model, the criteria are weighted regardless of what alternatives are considered. This fact allowed for a deep reflection on the process that was very useful in the analysis of results.

In order to reduce uncertainty and imprecision in the decision-making process, it is useful to carry out a sensitivity analysis, which takes into account those aspects that have attracted the most discussion.

Although the case study presented in this paper is relatively simple, AHP and ANP are designed to make complex decisions that

may contain a high number of criteria and alternatives. Environmental problems are characterized by having to analyze many factors and in many cases, numerous alternatives. The human mind has trouble managing more than 7 ± 2 concepts simultaneously. Therefore, the analysis of such problems through hierarchical or network models, allows breaking it down into parts, gathering it into small groups and focusing the mind of the DM in making comparisons of the elements in pairs. The comparison matrices are not excessively large and this allows the DM to manage all the information well. Although the DM has to answer numerous questions (especially ANP) all of them are very simple to answer, as shown in Tables 4 and 5.

Another advantage of AHP/ANP is that an ex post analysis of results of the decision-making process can be made, so the decision-making process is traceable, an issue that is highly valued by the DM.

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Appendix A. Pairwise comparison matrices. Hierarchy model

Table A.1

Judgment aggregation matrix for higher-level criteria.

	Economic criteria	Environmental criteria	Social criteria	Priority
Economic criteria	1	5.11	7.88	0.741
Environmental criteria	0.19	1	3.17	0.184
Social criteria	0.13	0.31	1	0.074

Table A.2

Judgment aggregation matrix for the economic criteria.

	C11	C12	C13	Priorities
C11	1	0.62	0.41	0.193
C12	1.60	1	0.43	0.268
C13	2.41	2.34	1	0.540

Table A.3

Judgment aggregation matrix for the environmental criteria.

	C21	C22	C23	Priorities
C21	1	0.75	1.18	0.318
C22	1.32	1	1.25	0.391
C23	0.85	0.80	1	0.291

Table A.4

BAT priority matrices with respect to the evaluation criteria.

	C11			C12			C13		
	BAT 1	BAT 2	BAT 3	BAT 1	BAT 2	BAT 3	BAT 1	BAT 2	BAT 3
BAT 1	1	4.05	7.76	1	3.62	6.19	1	6.80	0.32
BAT 2	0.25	1	1.90	0.28	1	1.71	0.16	1	0.11
BAT 3	0.13	0.53	1	0.16	0.58	1	3.08	8.96	1
	C21			C22			C23		
	BAT 1	BAT 2	BAT 3	BAT 1	BAT 2	BAT 3	BAT 1	BAT 2	BAT 3
BAT 1	1	2.01	1.33	1	3.26	0.16	1	4.76	0.41
BAT 2	0.50	1	0.53	0.31	1	0.11	0.21	1	0.13
BAT 3	0.75	1.89	1	6.14	8.66	1	2.45	7.69	1
	C31								
	BAT 1	BAT 2	BAT 3						
BAT 1	1	3.95	0.47						
BAT 2	0.25	1	0.12						
BAT 3	2.13	8.46	1						

Appendix B. Pairwise comparison matrices. Network model

Table B.1

Unweighted supermatrix.

		Alternatives			Economic criteria			Environmental criteria			Social criter.
		BAT 1	BAT 2	BAT 3	C11	C12	C13	C21	C22	C23	C31
Alternatives	BAT 1	0	0	0	0.73	0.70	0.28	0.44	0.17	0.30	0.30
	BAT 2	0	0	0	0.18	0.19	0.06	0.20	0.07	0.07	0.07
	BAT 3	0	0	0	0.09	0.11	0.66	0.36	0.77	0.63	0.63
Economic criteria	C11	0.69	0.20	0.30	0	0	0	0.10	0.07	0.14	0.15
	C12	0.13	0.68	0.13	0	0	0	0.68	0.29	0.53	0.22
	C13	0.18	0.12	0.58	0	0	0	0.22	0.65	0.33	0.63
Environmental criteria	C21	0.06	0.06	0.06	0.25	0.43	0.71	0	0	0	0.18
	C22	0.72	0.66	0.71	0.41	0.24	0.17	0	0	0	0.68
	C23	0.22	0.28	0.23	0.34	0.33	0.12	0	0	0	0.13
Social criteria	C31	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00

Table B.2

Weighted supermatrix.

		Alternatives			Economic criteria			Environmental criteria			Social criter.
		BAT 1	BAT 2	BAT 3	C11	C12	C13	C21	C22	C23	C31
Alternatives	BAT 1	0	0	0	0.46	0.44	0.18	0.28	0.10	0.19	0.19
	BAT 2	0	0	0	0.11	0.12	0.03	0.13	0.04	0.04	0.05
	BAT 3	0	0	0	0.06	0.07	0.41	0.22	0.48	0.40	0.40
Economic criteria	C11	0.51	0.15	0.22	0	0	0	0.03	0.02	0.04	0.02
	C12	0.10	0.50	0.09	0	0	0	0.19	0.08	0.15	0.02
	C13	0.13	0.09	0.43	0	0	0	0.06	0.18	0.09	0.07
Environmental criteria	C21	0.01	0.01	0.01	0.07	0.12	0.20	0	0	0	0.05
	C22	0.13	0.12	0.13	0.11	0.07	0.05	0	0	0	0.18
	C23	0.04	0.05	0.04	0.10	0.09	0.03	0	0	0	0.03
Social criteria	C31	0.07	0.07	0.07	0.09	0.09	0.09	0.09	0.09	0.09	0.00

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