Multicriteria Decision Making Methodologies Applied to the Selection of Best Available Techniques in the Ceramic Industry: Equalitarian vs Prioritised Weighting

V. Ibáñez-Forés, P. Aragonés-Beltrán and M. D. Bovea

1 Introduction

Traditionally it has been considered that technological development is a competitive advantage among companies, further promoting the economic growth and social benefit of countries [3, 4, 15].

Nowadays, one of the most common aims of the introduction of new technologies in industrial systems is the minimization of their negative effects on the environment [16]. This fact is being strengthened by the increasingly stringent environmental requirements imposed by European Commission through the continued implementation of environmental legislation (Directive 96/61/EC and Directive 2008/1/EC) [6, 7] (Integrated Pollution Prevention and Control–IPPC) and Directive 2010/75/EU [8] (Industrial Emissions Directive–IED)).

Specifically, in order to improve the sustainability of industries, the IED strengthens the application of Best Available Techniques (BAT). However, the numerous BAT that can be applied to the same sector make difficult to identify which is the optimal one for each industry. The BREF document (Reference Documents on Best Available Techniques) include all the BAT proposed by the European Commission which may apply to a particular industrial sector.

Over the last years, many studies were focused on the identification of the optimal technology options by using sustainability assessments and comparisons of

---

M. D. Bovea (✉) · V. Ibáñez-Forés
Departamento de Ingeniería Mecánica Y Construcción, Universitat Jaume I,
Av Sos Baynat s/n, 12071 Castellón, Spain
e-mail: bovea@uji.es

V. Ibáñez-Forés
e-mail: vibanez@uji.es

P. Aragonés-Beltrán
INGENIO (CSIC-UPV) Universitat Politècnica de València,
Camino de Vera s/n, C.P. 46022 Valencia, Spain
e-mail: aragones@dpi.upv.es

J. L. Ayuso Muñoz et al. (eds.), *Project Management and Engineering,* Lecture Notes in Management and Industrial Engineering, DOI 10.1007/978-3-319-12754-5_9

alternatives. Along this line, countless technology assessment methods have been created in order to support the decision-making processes [24].

On one hand, many authors considered that all sustainability indicators have the same relative importance and hence, they are equally weighted. Then, they directly compare the alternatives on the bases of their attributes, either numerically or graphically.

However, on the other hand, the technological choices are mostly multidimensional problems which have different demands, preferences or requirements in each one of its dimensions. Therefore, in order to identify the best option, it is needed to use multi-criteria methodologies which are based on the prioritization of the analysed indicators [5].

The most appropriate methodology to be applied in multi-criteria decision making varies almost exclusively with the characteristics of the problem [12]. As a consequence, choosing the best approach (equal weighting vs priority weighting) is a difficult decision.

The aim of this study is to analyse and compare both approaches by applying them to the identification of the most preferable BAT for the ceramic industry from an environmental, economic, technical and social perspective. To do so, two methodologies representing both approaches are applied to 13 alternative scenarios which were made up of different combinations of BAT. These combinations depend on the aim of each scenario: to improve energy efficiency, to mitigate particulate matter or acid gas emissions and to reduce noise. The selected multicriteria decision making methodologies are: an own methodology based on equal weighting of criteria and the Analytic Hierarchy Process (AHP), which is a widespread method based on priority weighting.

2 Configuration of Alternative Scenarios

Based on the standard process of manufacturing ceramic tiles in Spain (baseline scenario) 13 alternative scenarios are proposed, considering different combinations of BAT options and their optimum placement within the installation of the baseline scenario. Table 1 details the 9 BAT under study, which have been selected from the reference document for the ceramic industry [10].

The Fig. 1 shows the combination of BAT that constitute each alternative scenario. The details related to the scenarios configuration process, including all factors and physical parameters taken into account to optimize the combination of BAT, such as gas flow rates, operating temperatures or acid dew points, can be found at Ibáñez-Forés et al. [14].

Table 1 BAT options

Hot spot	BAT option		Type
Energy efficiency	1	1a	Heat recovery from dirty flue gasses (Heat exchangers)
		1b	Heat recovery from clean flue gasses (Heat exchangers)
Particulates (stack emissions)	2	2a	Traditional bag filters with pressure-pulse regeneration
		2b	High-temperature synthetic filter with pressure-pulse regeneration
	3		Electrostatic precipitator
Particulates (diffuse emissions)	4	4a	Full enclosure of bulk storage areas
		4b	Dust valves with suction and bag filter in bulk storage areas
		4c	Water spraying
Acid gases	5	5a	Cascade-type packed-bed adsorber with $CaCO_3$
		5b	Cascade-type packed-bed adsorber with a combination of $CaCO_3$ and $Ca(OH)_2$
	6		Module adsorber with several honeycomb modules made of $Ca(OH)_2$
	7	7a	Dry flue gas cleaning with $Ca(OH)_2$
		7b	Dry flue gas cleaning with $NaHCO_3$
	8	8a	Wet flue gas cleaning with $Ca(OH)_2$ or $CaCO_3$
		8b	Wet flue gas cleaning with $Na(OH)_2$
Noise	9		Enclosure of the noisiest units with noise-protection walls

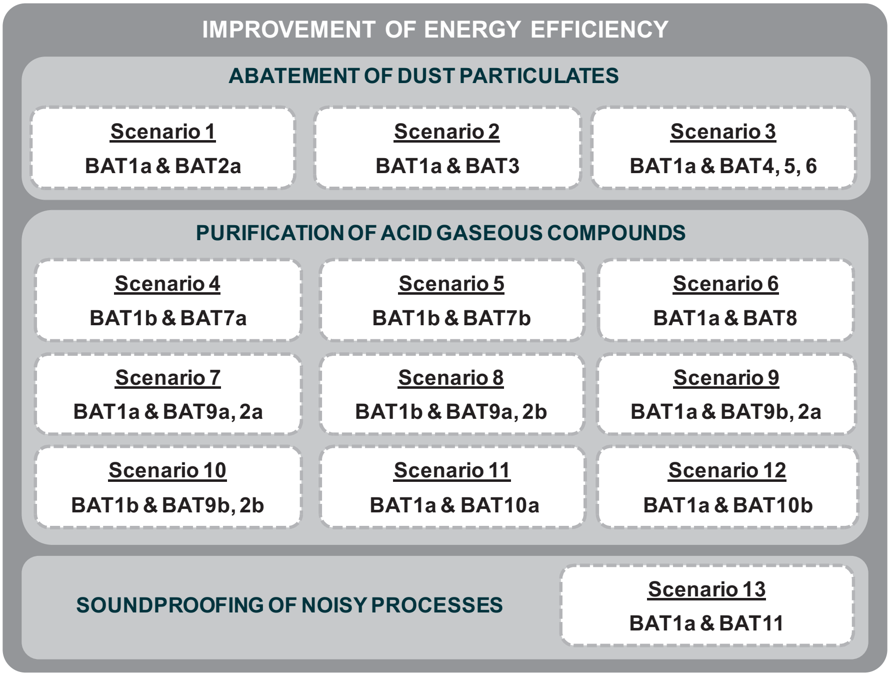

Fig. 1 Configuration of alternative scenarios

3 Sustainability Indicators

Table 2 describes the selected sustainability indicators which are grouped into environmental, economic, technical and social indicators. Moreover, Table 2 shows the scale and linearity of each indicator.

LCA software SimaPro v7.3.2 [23] and the Eco-Indicator 99 method [11] have been used to estimate the environmental indicator by modelling the inventory data.

Economic and technical indicators are based on secondary data, that is to say, data obtained directly from the literature, mainly from the reference document for the ceramic industry [10]. On the other hand, social indicators are obtained from primary data gathered by surveying different stakeholders related to the ceramic industry.

It should be noted, that the qualitative scoring method used for obtaining the qualitative indicators is based on scales shown in Table 3.

Furthermore, as there are two or more BAT in each scenario, the overall score of a scenario is calculated, for economic and technical indicators, as the average of the scores for all the BAT options that make up that scenario and, for social indicators, as the sum of the scores for the individual BAT options.

All information related to the calculation of the sustainability indicators, as well as the literature sources from which the relevant information were obtained, are detailed in Ibáñez-Forés et al. [14].

Below, Table 4 shows the sustainability indicators obtained for the alternative scenarios proposed (see Fig. 1).

4 Methodology Based on Equal Weighting of Criteria

The methodology applied to the identification of the most preferable scenario(s) based on equal weighting of criteria is divided in two stages: an initial screening which is carried out by comparing the scenarios on their economic performance and a graphical comparison of alternatives on all the sustainability indicators calculated.

4.1 Screening of Alternatives: Economic Viability Analysis

According to Schoenberger [21] the techniques that fulfil the requirements to be a BAT, but whose implementation is not economically feasible are called "*beyond BAT*" and they should only be applied to test scenarios aimed at developing them further to bring down their price.

Furthermore, according to the BAT costing methodology in the BREF on Economics and Cross-Media Effects [9], an investment is considered profitable when the pay-back period is equal to or shorter than 3 years, since it entails a quick recovery of investment and hence, it leads to a reduction in the risk of economic loss taken by the investor. Conversely, an investment is considered not profitable if the

Table 2 Description of the sustainability indicators selected

Indicators		Description	Unit	Linear
C1 Environment	C1.1 Eco-Indicator99	Eco-Indicator99 quantifies the overall environmental impact of a system by means of a single value that integrates the environmental impact for different impact categories	Points	Yes inverse
C2 Economic	C2.1 Investment Cost	Investment Cost (IC) is a quantitative measure which represents the initial payment needed to start up the equipment. Includes acquisition and installation costs and ancillary items such as insulation, connections, etc	€	Yes inverse
	C2.2 Total Annual Cost	The Total Annual Cost (TAC) incorporates the IC and operation and maintenance costs which include energy, materials and service expenses and fixed maintenance costs	€/year	Yes inverse
	C2.3 Net Annual Savings	Net Annual Savings (NAS) are calculated as the difference between TAC and the Avoided Costs (AC), which represent cost savings in raw materials, energy, labour, etc. owing to the implementation of BAT	€/year	Yes direct
C3 Technical	C3.1 Maintenance	Qualitative indicator that considers the requirements for maintenance, including the frequency and complexity involved as well as the related staff skills and training needed for the effective operation of the equipment	Qualitative	Yes inverse
	C3.2 Noise	Qualitative indicator that assesses the variations in noise level due to the application of BAT	Qualitative	Yes inverse
C4 Social	C4.1 Level of knowledge	Qualitative indicator that assesses the perception and predisposition of industry to adopt BAT through the knowledge that relevant experts have over them	Qualitative	Yes direct
	C4.2 Accessibility of BAT	Qualitative indicator that measures how reasonably accessible are the BAT and/or if they are applied relatively widely in industry	Qualitative	Yes direct

Table 3 Scores for different maintenance requirements, noise and level of knowledge/accessibility of BAT

Maintenance		Noise		Knowledge/accessibility	
Low	1	Reduction	−1	No application/no knowledge	1
Medium	2	Small or no change (<3 dBA)	0	Some application/some knowledge	2
High	3	Increase	1	Reasonable application/general knowledge	3
Very high	4			Wide-spread application/extensive knowledge	4

Table 4 Sustainability indicators

		Indicators							
		C1	C2			C3		C4	
		C1.1 (Pt)	C2.1 (€)	C2.2 (€/year)	C2.3 (€/year)	C3.1	C3.2	C4.1	C4.2
						(qualitative)			
Alternative scenarios	1	0.066	406,000	318,000	142,000	3	1	3.542	2.681
	2	0.067	3,150,000	620,000	−132,000	2	0	3.208	1.689
	3	0.065	348,000	157,000	331,000	1	1	3.743	2.645
	4	0.113	554,000	212,000	302,000	2	1	2.889	1.514
	5	0.115	554,000	246,000	279,000	2	1	2.889	1.514
	6	0.095	750,000	443,000	45,000	3	0	2.375	1.514
	7	0.068	959,000	378,000	82,000	3	1	3.181	1.764
	8	0.069	950,000	474,000	51,000	3	1	2.861	1.546
	9	0.068	959,000	419,000	41,000	3	1	3.181	1.764
	10	0.068	959,000	515,000	39,000	3	1	2.861	1.546
	11	0.068	1,817,000	548,000	−60,000	4	0	2.778	1.569
	12	0.069	1,817,000	553,000	−65,000	4	0	2.778	1.569
	13	0.069	196,000	119,000	369,000	1	−1	3.639	2.778

pay-back period is greater than the plant lifetime which, in this case, is assumed to be 15 years.

The pay-back period is defined as the period of time that the company needs to recover the initial Investment through the profits it generates and it can be calculated as the quotient between the initial Investment and the Net Annual Savings.

Therefore, to assess the profitability of each scenario in order to reject the non-profitable options, the pay-back periods are calculated for all scenarios and compared in the bar graph shown in Fig. 2. This graph includes two horizontal lines which represent the limit for the maximum profitability (green line) and for the economic unfeasibility (red line), respectively.

As it can be seen in Fig. 2, scenarios 1, 3, 4, 5, 7 and 13 are cost effective solutions since they have enough economic benefits to pay back the investment before ending their lifetime (15 years). At the other end, scenarios 6, 8, 9 and 10

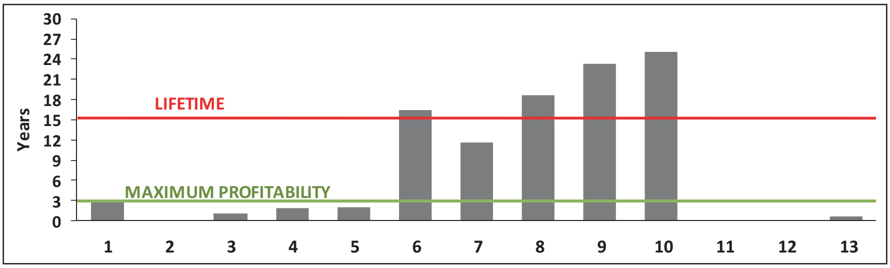

Fig. 2 Pay-back periods

have a pay-back period longer than their lifetime and hence they cannot be considered as economically feasible since the investment may be deemed irrecoverable. Therefore, those scenarios cannot pass to the next stage of the methodology and are screened out.

As shown in Table 4, scenarios 2, 11 and 12 have higher costs than the benefits of implementing them, therefore, they do not provide any Net Annual Savings for recovering the investment and consequently are also screened out from the analysis.

4.2 Comparison of Alternatives: Graphical Representation

Once the unprofitable scenarios have been rejected, the remaining options are compared for all the sustainability indicators considered. The different units in which the sustainability indicators are expressed (see Table 4) make it necessary to normalise them before comparing the alternatives, in order to ensure that all of them are in the same numeric order. To do so, the following approach has been adopted [2, 17, 20, 25]:

If a lower value of indicator is better:	*If a higher value of indicator is better:*
$z_{ij} = \frac{x_{ij} - x_{imin}}{x_{imax} - x_{imin}}$	$z_{ij} = \frac{x_{imax} - x_{ij}}{x_{imax} - x_{imin}}$

Where:

$i = 1, 2, \ldots, n$ – *number of sustainability indicators*
$j = 1, 2, \ldots, m$ – *number of alternative scenarios*
z_{ij} – *normalised value of ith indicator for the jth scenario*
x_{ij} – *value of ith indicator for the jth scenario (no normalised)*
$x_{imin} = min(x_{i1}, x_{i2}, \ldots, x_{im})$ – *minimum value of ith indicator for all scenarios*
$x_{imax} = max(x_{i1}, x_{i2}, \ldots, x_{im})$ – *maximum value of ith indicator for all scenarios*

In the following, the normalised values of the indicators for each scenario are plotted on a *spiderweb* graph, as it is shown in Fig. 3. These graphs represent the environmental, economic, technical and social behaviour of each alternative. As it is shown in these graphs, the scenario 13, followed by 4, 5 and 3, represent the most sustainable alternative since they have a better performance (smaller area) for all the considered indicators.

5 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) methodology, which was developed by Thomas Saaty in the 1970s [19], is a widely used technique to solve decision making problems involving multiple criteria. The AHP is one of the most used methods in that field due to its capacity to simplify complex decisions [18].

First of all, the Decision Maker (DM), the agent which holds the responsibility for making the final decision, has to be selected. In this case, the DM is a team of three industrial engineers with extensive experience in the ceramic industry. Although these experts have a deep knowledge of BAT due to their long experience in preparing Integrated Environmental Authorizations for ceramic industry, prior to beginning the process of decision making, they were fully informed about all the characteristics of the BAT considered.

It should be noted that the identification of the preferred scenarios is based on criteria/indicators which are linear and independent of each other (see Table 2), as it is assumed that there is not any interaction or influence between each other for any given property. These criteria have been agreed and considered by the DM as suitable for identifying sustainable scenarios.

Figure 4 shows the hierarchy structure which represents the decision-making problem, by representing the relationship established between the different criteria taken into account.

As it is described in Table 2, some of the criteria under consideration are qualitative, such as maintenance, noise, level of knowledge and accessibility of BAT. To configure the assessment matrix of the scenarios, the DM has to assess the scenarios with regard to each criterion based on their own knowledge and experience.

To do so, the individual preferences of the experts regarding the alternative scenarios for each criterion are measured by pair-wise comparison on the basis of the Saaty 1–9 scale [19].

Later on, from the results obtained from the pair-wise comparison, the assessment matrix is configured according to the methodology described by Saaty [19] (red box in Table 5). The different nature of data included in the assessment matrix (qualitative and quantitative), makes it needed to normalise them in a distributive manner to allow data comparison. It should be noted that these data reflect the preferences of DM, so it means that preferences are proportional to the values assigned to the alternatives for each criterion.

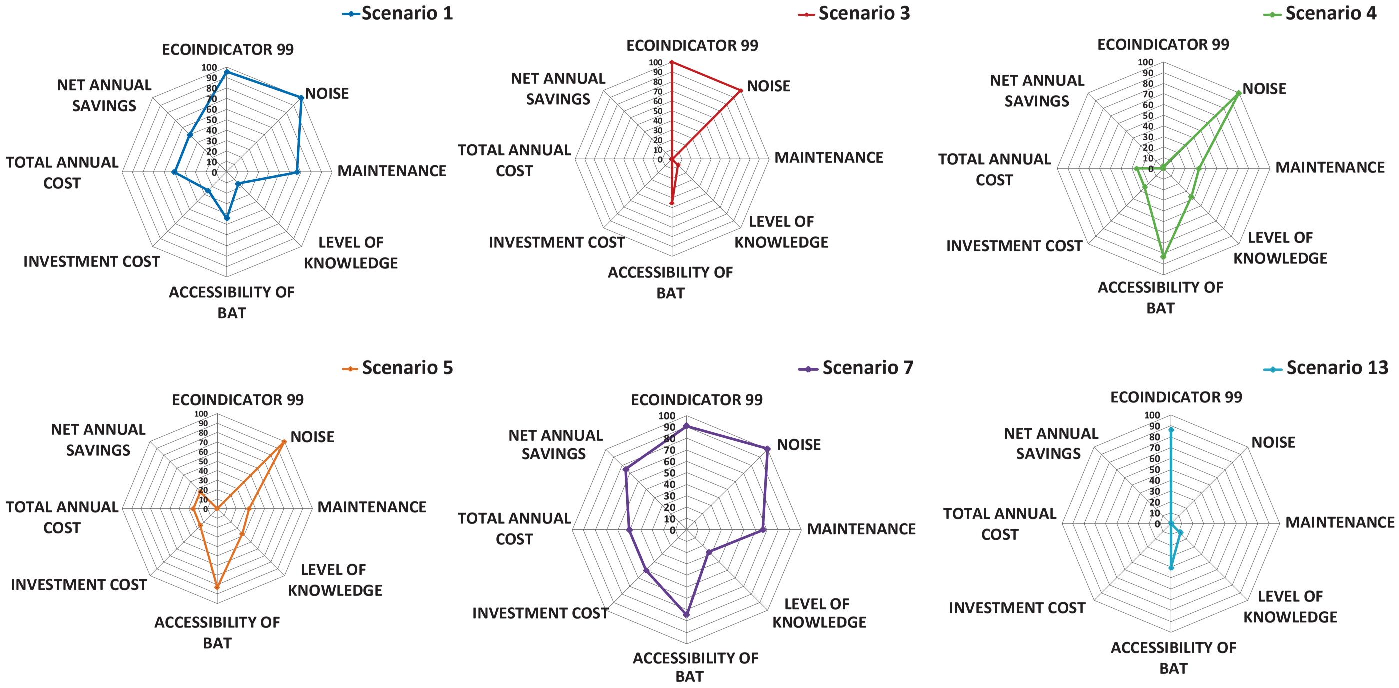

Fig. 3 Sustainability analysis (After normalisation, lower values are better for all indicators so that the smaller area bounded by the connecting lines on the diagram indicates a better scenario)

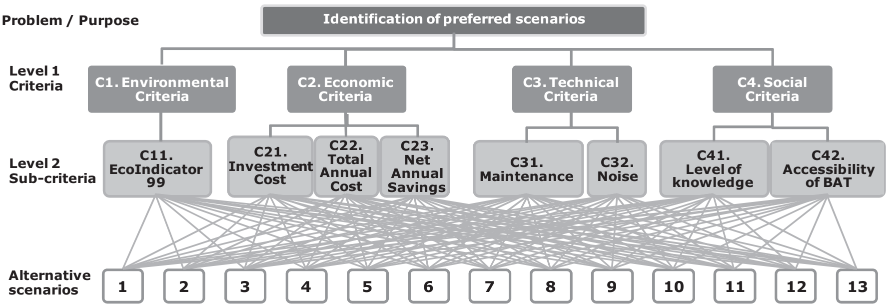

Fig. 4 Hierarchical decision model

Table 5 Final priority matrix of scenarios for decision making

		Criteria								
		C1	C2			C3		C4		
		C11	C21	C22	C23	C31	C32	C41	C42	
Sub-criteria global priority		0.064	0.080	0.340	0.171	0.040	0.190	0.047	0.068	Priority
Alternative scenarios	1	0.066	0.117	0.073	0.100	0.031	0.045	0.095	0.109	0.077
	2	0.067	0.015	0.037	−0.093	0.117	0.095	0.062	0.087	0.034
	3	0.065	0.137	0.147	0.232	0.031	0.203	0.098	0.115	0.157
	4	0.113	0.086	0.109	0.212	0.031	0.095	0.067	0.067	0.114
	5	0.115	0.086	0.094	0.196	0.031	0.095	0.067	0.067	0.107
	6	0.095	0.064	0.052	0.032	0.117	0.045	0.073	0.046	0.054
	7	0.068	0.050	0.061	0.058	0.031	0.045	0.077	0.082	0.058
	8	0.069	0.050	0.049	0.036	0.031	0.045	0.065	0.057	0.048
	9	0.068	0.050	0.055	0.029	0.031	0.045	0.077	0.082	0.051
	10	0.068	0.050	0.045	0.027	0.031	0.045	0.065	0.057	0.045
	11	0.068	0.026	0.042	−0.042	0.117	0.019	0.075	0.056	0.029
	12	0.069	0.026	0.042	−0.046	0.117	0.019	0.075	0.056	0.029
	13	0.069	0.243	0.194	0.259	0.287	0.203	0.105	0.119	0.197

Subsequently, according to Saaty [19], in order to weight the criteria, DM has to compare the relative importance of each criterion and sub-criterion on the basis of the Saaty scale. To do so, comparison matrices are filled by comparing pair-wise elements at each level of the hierarchy with respect to the upper-level element, based on the judgments of the DM. Therefore, according to Fig. 4, four matrices need to be filled: one for comparing the first level criteria (C1-environmental criteria, C2-economic criteria, C3-technical criteria and C4-social criteria) and three for comparing the sub-criteria within the same sub-criteria group (C21, C22 & C23; C31 & C32; and C41 & C42).

Since the DM is made up by a team of experts acting as a whole, the individual judgments were aggregated using the geometric mean [1, 13, 22].

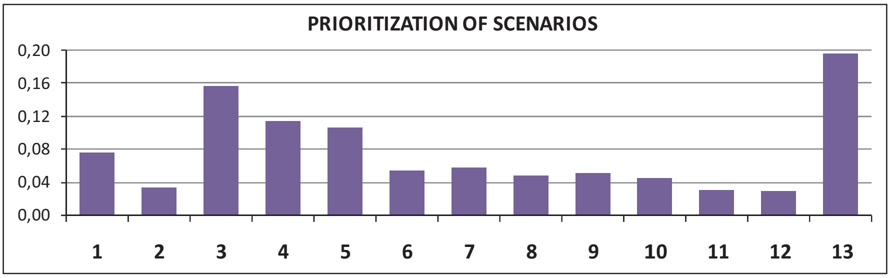

Fig. 5 Priority of scenarios based on the preferences of the decision maker

Note that the consistence ratio is $<5\,\%$, so the pair-wise comparison matrices, both individually and once aggregated, are regarded as consistent enough.

The overall priorities for each sub-criterion are shown in Table 5, in the row called “sub-criteria global priority”.

Lastly, the final priorities of the scenarios have been calculated by aggregating the individual priorities in additive way (weighted sum). These priorities are included in the last column of Table 5 and form the global priority vector for the lowest level of the hierarchy (see Fig. 3).

To facilitate the interpretation of the scoring resulted from the preferences of the DM, the global priority vector is represented in a bar graph which is shown in Fig. 4.

As it can be seen in Fig. 5, the preferable scenarios are, in order of priority, the 13, 3, 4 and 5.

6 Discussion and Conclusions

Comparing the results obtained from the application of the two methodologies considered, it can be found that the results obtained are similar in both cases.

Note that with the method based on equal weighting of criteria, although the results may vary depending on the interpretation of the output or graphs obtained, this method helps to identify the behaviour of each alternative for each indicator individually considered.

The AHP method is a more systematic method which allows better traceability. Furthermore, an order of priority of the alternatives is obtained by applying AHP. So, if the preferred option may not be applied, it would be known which is the next best option. However, the results obtained depend on the DM and hence, they are not generally applicable since if the DM varies, the preferred options may vary as well. In addition, as a consequence of the participation of the DM, which is usually made of to a group of experts with extensive knowledge in the involved field, the AHP method is a more costly and time-consuming process.

Regarding the case study, based on the results obtained from the application of both methodologies, it has been found that the most sustainable scenarios for the Spanish ceramic tiles industry combine heat recovery from flue gas with the abatement of its dust particulates (scenario 3) or with the soundproofing of noisy processes (scenario 13). Furthermore, to reduce the acid gaseous compounds from emissions, the most recommended sustainable scenarios include heat recovery from flue gas and its clean-up with $CaCO_3$ and/or $Ca(OH)_2$ (scenarios 4 and 5). These results are consistent, as have been obtained from the application of both multicriteria decision methodologies under study.

Acknowledgements The authors gratefully acknowledge the funding from the Spanish Ministry of Science and Innovation (DPI2008–04926/DPI) and the Generalitat Valenciana (ACOMP/2011/036).

References

1. Aczel J, Saaty TL (1983) Procedures for synthesizing ratio scale judgements. J Math Psychol 27:93–102
2. Afgan NH, Carvalho MG (2004) Sustainability assessment of hydrogen energy systems. Int J Hydrogen Energy 29:1327–1342
3. Afuah A (2000) How much do your "co-opetitors" capabilities matter in the face of technological change? Strategic Manage J 21:387–404
4. Azzone G, Manzini R (2008) Quick and dirty technology assessment: the case of an Italian research centre. Technol Forecast Soc Change 75:1324–1338
5. Bréchet T, Tulkens H (2009) Beyond BAT: selecting optimal combinations of available techniques, with an example from the limestone industry. J Environ Manage 90:1790–1801
6. Directive 1996/61/EC of the European Parliament and the Council, of 24 September, concerning integrated pollution prevention and control
7. Directive 2008/1/EC of the European Parliament and the Council, of 15 January, concerning integrated pollution prevention and control
8. Directive 2010/75/EU of the European Parliament and the Council, of 15 January, concerning Industrial Emissions
9. EC (2006) IPPC Reference document on economics and cross-media effects. European Commission, Institute for Prospective Technological Studies, Sevilla
10. EC (2007) IPCC Reference document on best available techniques in the ceramic manufacturing industry. European Commission, Institute for Prospective Technological Studies, Sevilla
11. Goedkoop M, Spriensma R (2000) The Ecoindicator'99: a damage oriented method for life cycle impact assessment: methodology report. Pré Consultants BV, Amersfoort
12. Gómez-López MD, Bayo J, García-Cascales MS, Angosto JM (2009) Decision support in disinfection technologies for treated wastewater reuse. J Clean Prod 17:1504–1511
13. Guzzo RA, Salas E (1995) Team effectiveness and decision making in organizations. Jossey-Bass, San Francisco
14. Ibáñez-Forés V, Bovea MD, Azapagic A (2013) Assessing the sustainability of best available techniques: methodology and application in the ceramic tiles industry. J Clean Prod 51:162–176
15. Liao Z, Cheung MT (2002) Internet-based e-banking and consumer attitudes: an empirical study. Inf Manage 39:283–295
16. Musango JK, Brent AC (2011) A conceptual framework for energy technology sustainability assessment. Energy Sustain Dev 15:84–91

17. Pilavachi PA, Roumpeas CP, Minett S, Afgan NH (2006) Multi-criteria evaluation for CHP system options. Energy Convers Manag 47:3519–3529
18. Pilavachi PA, Stephanidis SD, Pappas VA, Afgan NH (2009) Multi-criteria evaluation of hydrogen and natural gas fuelled power plant technologies. App Therm Eng 29:2228–2234
19. Saaty TL (1980) The analytic hierarchy process. McGraw-Hill, New York
20. Sadiq R, Khan FI, Veitch B (2005) Evaluating offshore technologies for produced water management using GreenPro-I: a risk-based life cycle analysis for green and clean process selection and design. Comput Chem Eng 29:1023–1039
21. Schoenberger H (2011) Lignite coke moving bed adsorber for cement plants e BAT or beyond BAT?. J Clean Prod 19:1057–1065
22. Schrage M (1995) No more teams!: mastering the dynamics of creative collaboration. Currency Doubleday, New York
23. Simapro v7.3.2 (2011) PRé Consultants, Amersfoort
24. Tran TA, Daim T (2008) A taxonomic review of methods and tools applied in technology assessment. Technol Forecast Soc Change 75:1396–1405
25. Wang JJ, Jing YY, Zhang CF, Shi GH, Zhang XT (2008) A fuzzy multi-criteria decision-making model for trigeneration system. Energy Policy 36:3823–3832