ENVIRONMENTAL IMPACT OF POWER PLANTS: COMPARATIVE CRITERIA OF EVALUATION

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ABSTRACT

In the environmental impact assessments the different designing hypothesis must be selected and classified, taking into account any method the decider considers important. The result of the evaluation process depends on the adopted criteria, often incompatible, which therefore must be chosen with great care and, as far as possible, with objective methodologies.

The purpose of this paper is a comparison among different approaches, suitable for several typologies of works, in order to choose the designing alternatives concerning power stations. A sample of multi-criterion analysis was applied to a strategic environmental assessment (the Italian VAS procedure) comparing three plans of power plants, which obtained the compatibility judgment within the environmental impact assessment (the Italian VIA procedure). In order to identify the solution that minimizes the environmental effects and at the same time to optimize the technical and economic benefits, the study of the most considerable parameters in the decision process was carried out, with particular attention to the impacts on environment and public health and to the socio-economic consequences.

INTRODUCTION

Comparison and choice among various alternatives by means of different criteria of evaluation, often conflicting, are delicate tasks from which who is involved in environmental impact assessments cannot help to deal with. In order to select the solutions that can be technically and economically carried out and to classify them taking into account all the criteria considered by the decision maker, different methods were implemented, applicable to several contexts.

For any adopted method, the final result depends considerably on the assumed evaluation criteria, which therefore must be chosen very carefully, trying to examine all the significant factors.

In the present paper the choice of the “best” alternative was done through a multi-criterion approach. The main methods used in order to solve the decision problem were described; such general methods can be adopted both in the environmental impact assessment (in Italy: VIA procedure) and in the strategic environmental assessment (VAS procedure). Afterwards an application sample was shown, representing a methodological approach to the planning scenario of VAS procedure. The sample is only a comparative analysis limited to three plans of power plants, which passed with positive judgment the VIA procedure. This work aims at showing how the multi-criterion analysis can be extended from the particular view of VIA to that most general one of VAS.

EVALUATION METHODS

The main approaches to the decision problem, generally used within a VIA procedure, are the classic multi-criterion analysis, the hierarchical analysis and the ELECTRE methods. For such assessment methodologies, the logic according to which the problem is set up, the significance of the steps, the advantages and the limits (both conceptual and operative), the different phases and the typologies of plan for which they are more suitable were studied.

Classic multi-criterion analysis

The “classic” multi-criterion analysis (Keeney and Raiffa, 1976) is a methodology of approach to the decision problem that permits to produce an ordering of the alternatives: a score which measures the performances regarding all considered criteria is attributed to each examined solution.

The procedure is based on the construction of the evaluation matrix (Matrix 1), having as many rows as the criteria and as many columns as the alternatives. The matrix elements $g_i(k)$ (i row, k column) represent the indices or the impacts of the A_k alternative (k column) regarding the C_i criterion (i row). The index of an alternative concerning a criterion is the estimate of the same criterion once the alternative were achieved, while the impact is the difference between such estimate and the value that would be had if the alternative were not achieved. Generally the use of indices is preferred, since they supply more information.

Matrix 1 – Structure of an evaluation matrix

	A_1	A_2	…	A_k	…
C_1	$g_1(1)$	$g_1(2)$	…	$g_1(k)$	…
C_2	$g_2(1)$	$g_2(2)$	…	$g_2(k)$	…
…	…	…	…	…	…
C_i	$g_i(1)$	$g_i(2)$	…	$g_i(k)$	…
…	…	…	…	…	…

In an evaluation matrix, to each C_i criterion a specific v_i utility function must be associated. The application of this function permits to obtain, from each element of the i row, a value usually comprised between 0 and 1, where 1 expresses maximum “satisfaction” and 0 maximum “dissatisfaction” for the performance of the corresponding alternative regarding the considered criterion. For each A_k alternative, the $g_i(k)$ values of the indices concerning each criterion are therefore turned into $v_i g_i(k)$ values, which measure the performance of the alternative regarding the different criteria and are generally ordered in a second matrix (Matrix 2), having the same dimensions of the evaluation matrix.

Matrix 2 – Evaluation matrix after the application of the value-function

	A_1	A_2	…	A_k	…
C_1	$v_1\,g_1(1)$	$v_1\,g_1(2)$	…	$v_1\,g_1(k)$	…
C_2	$v_2\,g_2(1)$	$v_2\,g_2(2)$	…	$v_2\,g_2(k)$	…
…	…	…	…	…	…
C_i	$v_i\,g_i(1)$	$v_i\,g_i(2)$	…	$v_i\,g_i(k)$	…
…	…	…	…	…	…

To each C_i criterion a peculiar w_i weight must be attributed, representing the relative importance regarding the other criteria. The corresponding W weight vector should be defined by the decider, in order to reflect the structure of his preferences; the procedure for obtaining the weight vector rigorously is often complex.
After the definition of weights, the $V(k)$ total performance of each A_k alternative is calculated as weighed sum of its performances regarding each criteria C_i:

$$V(k)=w_1\,v_1\,g_1(k)+w_2\,v_2\,g_2(k)+\ldots+w_i\,v_i\,g_i(k)+\ldots \qquad (1)$$

In Matrix 3 the total performances are reported, for each alternative, in the respective column (last row), together with the partial performances, shown in the same column, and the weights associated to the criteria (reported in the weight column).

Matrix 3 - Matrix of total performances

	A_1	A_2	…	A_k	…	W
C_1	$v_1\,g_1(1)$	$v_1\,g_1(2)$	…	$v_1\,g_1(k)$	…	w_1
C_2	$v_2\,g_2(1)$	$v_2\,g_2(2)$	…	$v_2\,g_2(k)$	…	w_2
…	…	…	…	…	…	…
C_i	$v_i\,g_i(1)$	$v_i\,g_i(2)$	…	$v_i\,g_i(k)$	…	w_i
…	…	…	…	…	…	…
V	V(1)	V(2)	…	V(k)	…	

Finally, on the basis of the total performances, the alternatives can be ordered: the first one has the higher score and the following ones present gradually decreasing scores. The result depends on the assigned weight vector and reflects therefore the decider's subjectivity. In this case a sensitivity analysis appears very useful, in order to evaluate how the solution changes by modifying the weights and to determine the solidity of the ordering obtained with a specific weight vector.
Formally the classic multi-criterion analysis is the only rigorous method and supplies a complete ordering of the alternatives. However such approach is based on hypotheses (separability and additivity) that are not easily verified in actual cases; besides it needs a complex interaction between who carries out the analysis under the technical point of view and the decider (estimate of utility function and weight vector).
The classic multi-criterion analysis is suitable for solving very structured problems, in a phase of the decision process in which the greatest part of the evaluation can be achieved in a quantitative way.

Hierarchical analysis
Also hierarchical analysis (Saaty, 1986; Vargas and Kats, 1990) is a methodology that expresses the total performances of different alternatives by attributing to each of them a score obtained as weighed sum of the performances regarding each criterion.
The method is divided in three phases:

1) decomposition;
2) pair comparisons;
3) hierarchical resetting.

The decomposition consists in the definition of a hierarchical structure, including:

a) a starting level, that represents the general objective (for example, to select "best" alternative);
b) a final level, that expresses the alternatives;
c) a series of intermediate levels, representing several criteria and under-criteria.

In the simplest case the hierarchy has three levels (Figure 1):

1) general objective (O);
2) criteria (C_i);
3) alternatives (A_k).

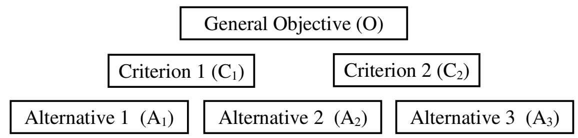

Figure 1 – Three level hierarchy: general objective, criteria and alternatives

The elements of the hierarchy undergo pair comparisons: each element of each level is compared with the other elements of the same level according to each criterion of the upper level. The decider must answer questions such as: "how much *i* alternative is better than *j* alternative under the point of view of *k* criterion?", or: "how much *l* criterion is more important than *m* criterion regarding the general objective?". The answer can be quantitative, but since not always this is possible, Saaty's relative importance scale (Table 1) provides that also qualitative answers can be expressed as numerical values.

Table 1 – Saaty's relative importance scale for pair comparisons

Preference i/j	**Numerical value**
Equal	1
Weak	3
Significant	5
Strong	7
Absolute	9
Intermediate values	2, 4, 6, 8

The m_{ij} answers of the decider are reported in pair comparison matrices (Matrix 4), where the preference of *j* in respect to *i* is the reciprocal value of the preference of *i* in respect to *j*. They are square matrices having dimensions equal to the number of elements of the considered hierarchical level.

Matrix 4 – Structure of a pair comparison matrix

C_i	A_1	A_2	A_3
A_1	1	m_{12}	m_{13}
A_2	$1/\,m_{12}$	1	m_{23}
A_3	$1/\,m_{13}$	$1/\,m_{23}$	1

For each hierarchical level as many pair comparison matrices must be generated as the elements of the upper level. Each matrix permits to order the elements of the considered hierarchical level regarding the single involved criterion, that belongs to the upper level.
A pair comparison matrix is "consistent" when three generic elements m_{ij}, m_{ik}, m_{jk} verify the following equation:

$$m_{ik} = m_{ij} \cdot m_{jk} \qquad (2)$$

If the considered matrix is consistent, it reflects an exact modelling of the decider's preferences and the ordering vector is the dominant auto-vector of the matrix (proportional to each

column). Since the decider's answers are inevitably approximated, pair comparison matrices are often not consistent. The inconsistence is almost unavoidable if the decider uses Saaty's relative importance scale, since it has an upper limit. For small consistence error, Saaty proposed approximate methods in order to approach the dominant auto-vector.
After the calculation of the ordering vectors for each level regarding the elements of the upper level, it is possible to come back along the hierarchy in order to determine the total ordering vector for the alternatives regarding the general objective. For a three level hierarchy, the obtained ordering vectors concern the alternatives regarding each criterion and the criteria regarding the general objective. The score attributed to an alternative in the total ordering vector is the weighed sum of the elements of the same alternative ordering vector regarding the criteria, where the weights are the elements of criteria ordering vector regarding the general objective.
Under the mathematical point of view, hierarchical analysis is more complex than classic multi-criterion analysis, but it aims at simplifying the interaction with the decider, who answers simpler and same type questions (pair comparisons); besides, it allows to express preferences in a qualitative way. A limit of hierarchical analysis is the introduction of subjective elements, such as the choice of relative importance scale, in case of qualitative evaluations, or the definition of acceptable inconsistence limit and ordering vector, in case of inconsistence. Moreover the final ordering depends on the considered plans and can change (rank reversal) with the introduction of insignificant alternatives.
The hierarchical analysis permits also qualitative estimates and therefore is suitable for preliminary phases, when the judgment of experts is more frequent than the use of quantitative models.

ELECTRE methods

The rigorous mathematical axioms appear unsuitable for describing the complexity of decision processes. The purpose of ELECTRE methods (ELimination ET Choix Traduisant the REalité; Roy, 1993; Maystre ET al., 1994) is to achieve an approach being the most possible in harmony with the common sense of actual choices, even if it maintains some incoherences under the mathematical point of view.
Classic multi-criterion analysis and hierarchical analysis are compensation methods, where a deficiency in a criterion can always be balanced with a suitable benefit in another one. ELECTRE methods, instead, provide that incomparableness can exist, that is to say impossibility to establish a relation of preference or indifference in a comparison. The choice is carried out among comparable options, belonging to the same category. Besides, ELECTRE explicitly considers that the discrimination faculty can be finite. These hypotheses make the transitivity of preferences fail.
ELECTRE methods are based on the overclassing conception. The A_i alternative outclasses the A_j when there are valid reasons to prefer the first alternative. For the existence of the overclassing relation both favourable or not opposing reasons (agreement) and contrary reasons (disagreement) must be considered. In order to calculate agreement and disagreement it is necessary to have a monotonic evaluation matrix (each index must be maximized or minimized to obtain the maximum of satisfaction) and a weight vector that expresses the relative importance of the criteria. Differences about calculation and integration of agreement and disagreement and about the final result of the analysis exist.
Since not always an overclassing relation is possible for a pair of alternatives, ELECTRE generates an incomplete overclassing graph. Because of the incomparableness and intransitiveness, it cannot be obtained an ordered set, but only a "nucleus" of incompatible alternatives which cannot be discard, as no other alternative of the nucleus outclasses them. Therefore it is not possible to speak about "best" alternatives, but about alternatives that can be discarded and alternatives that are candidates to the choice.
The final ordering depends on the considered alternatives, like in the hierarchical analysis, and, because of the incomparableness, on the calculation way. Some simplifications introduced by ELECTRE methods are only apparent: weights are used without analyzing the assignment modalities and the utility functions are eliminated by postulating monotonic evaluation matrices. Moreover the final result depends strongly on parameters having no exact physical significance and arbitrarily fixed values.
The remarks about the characteristics of the described evaluation methods are summarized in the following table (Table 2).

Table 2 – Main characteristics of the classic multi-criterion analysis (MCA), hierarchical analysis (HA) and ELECTRE methods

	MCA	HA	ELECTRE
Result	Score for each alternative; Complete ordering	Score for each alternative; Complete ordering	Nucleus; Partial ordering
Mathematical precision	Yes	Not rigorous weights assignment; Arbitrary choice of qualitative scale	Arbitrary assignment of some limits
Rank reversal	No	Dependence on insignificant alternatives	Dependence on insignificant alternatives
Accordance with actual decision process	Prevailing theoretical aspect	Prevailing theoretical aspect, but admitted decider's inconsistence	Close to common sense; Admitted incomparableness
Simplicity for decider	Complex questions	Simple but numerous questions	Yes
Transparency for decider	Possibility to understand each step	Arbitrary choice of qualitative scale	Arbitrary assignment of some limits; Mathematical complexity
Possibility to deal with qualitative data	Qualitative data must be expressed as quantitative data	Excellent	Good

HIERARCHICAL ANALYSIS APPLIED TO CCGT POWER PLANT

Using the instruments of multi-criterion analysis the decision problem concerning the choice among three alternative plans of typical CCGT (Combined Cycle Gas Turbine) power plants was examined. The adopted evaluation methodology was the hierarchical analysis by Saaty (HA), which is one of the most operative methods in cases involving multiple actions and criteria, permits to make clear calculation of the parameters and allows to carry out also qualitative estimates.
Such approach can be useful in a perspective of VAS procedure.

Alternative plans

The examined power stations obtained the compatibility judgment at the end of the Italian national environmental impact assessment (VIA). Their comparison according to the hierarchical analysis method must be considered as a sample of procedure for a comparative analysis of different plans, situated in distant areas. The three hypotheses are:

1) CCGT power plant, total power: 750 MWe, fed with natural gas, site: Termoli (Centre-South Italy), approved with DM 03/09/2002;

2) CCGT power plant, total power: 385 MWe, fed with natural gas, site: Portogruaro (North Italy), approved with DM 22/10/2002;

3) CCGT power plant, total power: 750 MWe, fed with natural gas, site: Aprilia (Centre-South Italy), approved with DM 22/01/2004.

Definition of actions

The studied scenario included the perturbations induced by each power station. For this typology of works VIA procedure demand an extension of 5 km from the site.

Concerning the temporal definition of the plan actions, they are related to construction and working phases. In order to apply HA method to three CCGT plants, the impact scene had to be simplified: the examination of all the aspects, also the less significant ones, would have produced a very complex analysis and a choice of weights unsuitable for reality.

The identification and the selection of objectives were the bases to define a hierarchy of consistent subordination. In the hierarchy of impact subordination each plan was considered in its totality; for some aspects, however, it was chosen to separate the contributions of the plant from those of the complementary works (feeding gas pipe-line, transfer electric power line).

As regards the temporal characterization of the expected impacts, in many cases it was chosen to neglect the yard phase (except, as an example, for the evaluation of the occupation implications), because it is very limited regarding the plant working life (approximately 2 years against 25÷30 years) and usually is characterized by modest effects.

Hierarchical decomposition

The phase of decomposition consisted in the definition of a hierarchical structure. Objectives that must be achieved in order to reduce negative impacts produced by the plan were identified. They were derived from the main objective or "root" (the choice of the "best" plan), divided in more detailed sub-objectives ("branches" and "leaves"). The construction of the hierarchy began from a purpose list, widened in more and more specific objectives, as a result of a preliminary evaluation of impact elements concerning the examined typology of works. The procedure considered both the analyses of different specialist and the cares of the involved subjects.

The three CCGT power stations followed completely independent procedures and passed the judgment of several experts within the VIA commission. The judgment, oriented to the definition of the "environmentally compatible" plant, could be based on a hierarchical structure in order to make the procedure objective. Experts in different matters could characterize the main impact elements for each category of works and adopt the relative hierarchy in order to direct the proposers towards the less impacting alternative.

The VAS procedure became part of this view. In the present paper a hierarchy was defined, being the result (or the compromise) of the indications supplied by specialists of the interested fields (Figure 2).

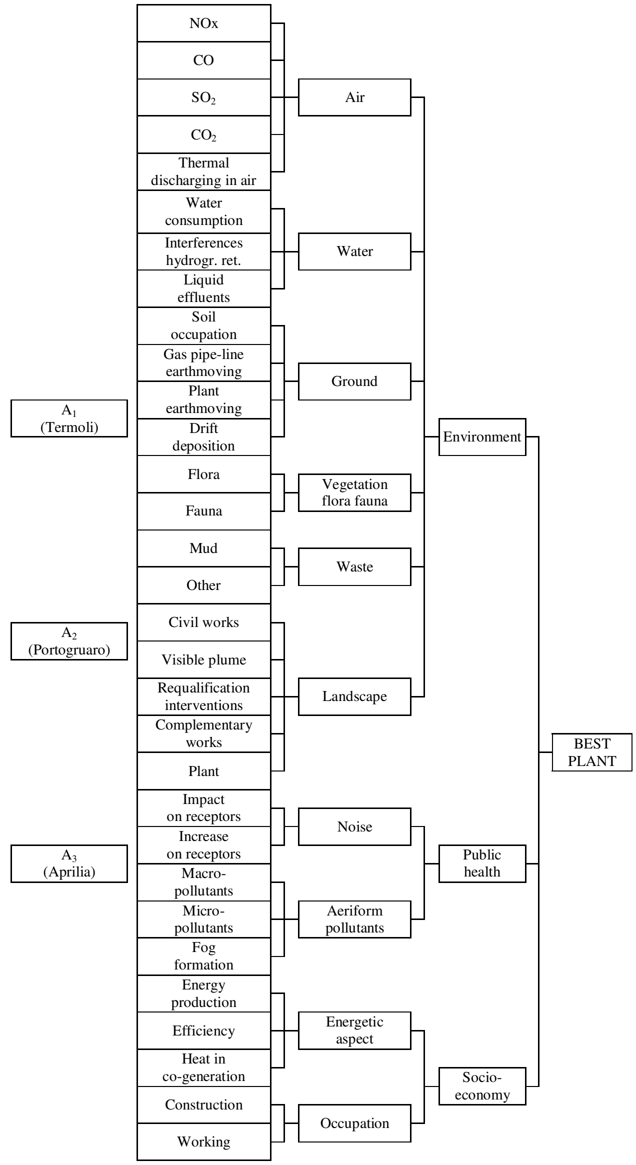

Figure 2 – Objectives hierarchy

Such a hierarchy consisted of four levels:

1) the "super-objective" (choice of the "best" solution);

2) the objective to reduce the interferences on environment and public health and to maximize the socio-economic benefits;

3) the objective to reduce the impacts on air, water, etc. (environment sub-objectives) and the negative effects produced by noise and aeriform pollutant (public health sub-objectives); the objective to maximize the energetic aspects and the occupation (socio-economy sub-objectives);

4) the objective to reduce the emissions of NO_x, CO, SO_2, CO_2 and the thermal discharge on the air (air sub-objectives), etc., till the objective to maximize the production of energy, the efficiency and the heat exported in co-generation regimen (energetic aspects sub-objectives).

To the defined four levels the three alternative plans (Termoli, Portogruaro and Aprilia) were added.

A comparison on the basis of quantitative information was preferred, being purged from subjective judgments.

Analytically it meant to have consistent matrices, reflecting an exact modelling of the decider's preferences. In the present work indices were often used, characterizing a phenomenon in physical units, and, when unavoidable, comparisons in qualitative terms were carried out. The qualitative evaluation was necessary in order to define the relations among the four hierarchical levels. A value-function for each criterion was produced, asking experts to estimate the relations of importance among the criteria of their competence. The comparison was carried out by using the Saaty's method (Table 1) and 44 criteria on three levels were examined.
As an example, the last level towards the super-criterion "best plant" consisted in three criteria: 1) to minimize the impact on environment; 2) to minimize the impact on public health; 3) to maximize the socio-economic benefits. Even if the abstraction to this point of the procedure was very high, the comparisons summarized in Matrix 5 were carried out.

Matrix 5 – Pair omparison matrix of the last level criteria regarding the super-criterion "best plant"

BEST PLANT	Environment	Public health	Socio-economy
Environment	1	1/4	1/3
Public health	4	1	2
Socio-economy	3	1/2	1

Finally the weight vector associated to the three criteria (Matrix 6) was defined and the estimated error, relatively low, showed that, even in case of inconsistence, the decider expressed a not conflicting judgment.

Matrix 6 – Weight vector associated to the last level criteria regarding the super-criterion "best plant"

BEST PLANT	W_I
Environment	0.127
Public health	0.530
Socio-economy	0.343

Hierarchical resetting

Once the ordering vectors for the different levels were obtained, the hierarchical resetting attributed to each plan a score, equal to the weighed sum of the performances calculated along each way, with the purpose of determining the total ordering of the alternatives regarding the super-criterion.
In order to come back along the hierarchy and to evaluate the performances of the three power stations concerning "air", for example, the corresponding matrix of alternatives' ordering, made by weight vectors regarding each IV level criterion, was multiplied for: a) the ordering vector regarding the III level criterion "air"; b) the "air" weight in the ordering vector regarding the II level criterion "environment"; c) the "environment" weight in the ordering vector regarding the super-criterion.
Operating in such a way for all different criteria and adding the obtained values, a relative score was assigned to the super-criterion and finally the "best" plant was selected (Table 3).

Results

The hierarchical analysis method (HA) demonstrated that differences among the three plants subjected to comparative evaluation are not wide. However, according to the obtained scores (Table 3), Aprilia plan (A_3) guarantees better performances than the alternative solutions.
The data can be interpreted considering that A_3 does not interfere with the hydrographical reticulum and does not produce the visible plume of steam, thanks to the choice of air cooling.

Table 3 – Scores of the three alternatives regarding the performances of the last level and the super-criterion

Alternative	Site	Environment performance	Public health performance	Socio-economy performance	BEST PLANT
A_1	**Termoli**	0.021	0.074	0.154	**0.249**
A_2	**Portogruaro**	0.045	0.192	0.061	**0.299**
A_3	**Aprilia**	0.060	0.265	0.128	**0.453**

Also concerning the public health, Termoli (A_1) and Portogruaro (A_2) have scores a little lower than Aprilia, which, taking advantage of dominant winds, presents a wider dispersion of pollutants.
Under the socio-economic point of view, Termoli guarantees the best performances, since it benefits from the best efficiency, the best practicability of the plan of heat release in co-generation (CHP) and the best consequences on the occupation. On the contrary, Portogruaro feels the effects due to the inferior power size (385 MWe rather than 750) and to the geographical area lacking in occupation problems.
Finally, all things considered, the response supplied by Saaty's hierarchical analysis method was that A_3 solution (Aprilia) succeeds in reducing the environmental and human costs and maximizing the energetic-economic benefits, therefore it is the preferable alternative on the bases of the carried out comparison. This result was obtained by means of a multi-criterion analysis process, limited to the comparisons among three plans. A sensitivity analysis, evaluating the ordering stability regarding the introduced arbitrary elements, can contribute to the validation of such an approach to the decision problem.

CONCLUSIONS

In the present paper a methodological approach to the choice of alternative plans for CCGT power plants was attempted, in order to apply it to a higher level than the one of environmental impact assessments (Italian VIA). VIA procedure is limited to the characterization and reduction of the negative environmental effects of a single work in a precise localization. It is therefore an instrument of control external to the planning; on the contrary, the strategic environmental evaluation (Italian VAS) has a double valence, of control and programming.
The analysis carried out in this paper aims at meeting the two levels (VIA and VAS) by allowing the evaluation of alternative plans, typical of VAS procedure, with the detail of VIA. The comparison of the alternatives by means of multi-criterion analysis would permit a hypothetical decider (regional or national) to plan the "best" works and to send back or to refuse the ones having lower performances.
Among the different methods of multi-criterion analysis the hierarchical analysis by Saaty (HA) was chosen, since it is very suitable for dealing with problems involving qualitative data. The numerical values obtained in pair comparisons must be considered a compromise within the group of technicians called to operate the choice. Such a choice is sufficiently purged from subjective conditionings due to total examination. By separating a complex problem (choice of the "best" solution) in a sequence of simpler problems and solving them by pairs, the decision process is simplified and a transparent analytical way is obtained, practicable and repeatable in every

single part.

The examined alternative plans were three combined cycle power stations that obtained the environmental compatibility judgment. The previous remarks can be generalized and are valid also for comparisons among alternative plans of other work typologies (roads, dams, airports, etc.), as long as significant interactions and territorial context be considered.

NOMENCLATURE

A_k	k alternative
C_i	i criterion
$g_i(k)$	index/impact of A_k regarding C_i
v_i	utility or value-function concerning C_i
$v_i\, g_i(k)$	performance of A_k regarding C_i
w_i	weight associated to C_i
W	weight vector
$V(k)$	total performance of A_k
V	total performances vector
m_{ij}	preference of i regarding j in pair comparisons

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