Dealing with a multiple criteria environmental problem with interaction effects between criteria through an extension of the Electre III method

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Abstract

In this article we compare five alternative projects for the requalification of an abandoned quarry. The starting point for this paper was a request made by a decision maker. It was not for help in making a decision as such, but rather for a comparison of different projects. In particular, we are interested in ranking the considered projects on the basis of six different criteria. An extension of the Electre III method with interactions between pairs of criteria was applied in the research. A focus group of experts (in economic evaluation, environmental engineering, and landscape ecology) was formed to be in charge of the process leading to the assignment of numerical values to the weights and interaction coefficients. We report on the way the process evolved and on the difficulties we encountered in obtaining consensual sets of values. Taking into account these difficulties, we considered other sets of weights and interaction coefficients. Our aim was also to study the impact on the final ranking of the fact that these numerical values, assigned to the parameters, were not perfectly defined. This allowed us to formulate robust conclusions which were presented to the members of the focus group.

Keywords: Multiple criteria analysis, Group decisions and negotiations, Decision Support Systems, Electre methods, Interaction between criteria.

1. Introduction

The starting point of the work presented in this article comes from a request made by a decision maker. It was not for help in making a decision as such, but rather for a comparison of five requalification actions or projects for an abandoned quarry. In addressing the problem for study, the comparison has to take into account several stakeholders' different points of view. To do so, an adequate and coherent family of criteria has to be built. The authors of the current study had good reasons to think that in a context of sustainability assessment they should not discard *a priori* the possibility of interactions between some pairs of criteria. Indeed, in the context of

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sustainability assessment, economic sustainability has an economic cost and ecological sustainability has an ecological cost (Munda, 2005). Following this reasoning, it is possible to state that in the particular context of sustainability assessment the different aspects (required for the construction of criteria) usually interact with each other, reflecting the natural dynamics of environmental and land-use territorial systems. Consequently, it seemed justified to try to highlight potential synergies, redundancies, or other phenomena among coalitions of criteria.

Given the possible existence of interaction between some pairs of criteria, we undertook a detailed overview of the main approaches used in the literature to consider the evaluation of interaction effects. This analysis led to the choice of an extension of Electre III with interactions (Figueira et al., 2009), which has proved to be an appropriate method (*cf.* Section 2, below). The comparison of five alternative requalification projects for an abandoned quarry (*cf.* Section 3) seemed to the authors a very good opportunity to test this extension of Electre III. Of particular interest was the question of whether with this method it was possible to highlight and build robust conclusions, taking into account the existence of some arbitrariness when assigning values to the main parameters (weights of criteria and interaction coefficients). To assign numerical values to these parameters and to implement the method in general, it was necessary to form a focus group (*cf.* Section 3). Section 4 reports the way the focus group worked. Section 5 provides the results of the application and discusses the findings through a sensitivity analysis, which enabled us to highlight and build robust conclusions. Finally, Section 6 contains the main conclusions that can be drawn from the research.

2. Adopting an MCDA method to handle interaction between criteria

When the analyst was confronted with this case study, he had good reasons to believe that he should take into account the interactions between criteria (this was later confirmed, see Section 3). Under these conditions, the choice of a multiple criteria approach was examined. Thus, the multiple criteria methods taking into account interaction between criteria were reviewed to adopt a suitable one.

There is currently a great variety of multiple criteria decision aiding (MCDA) methods and this means that the task of adopting the appropriate method for a certain decision-aiding situation is not an easy one (see Roy and Słowiński, 2013). There are also a certain number of methods considering the interaction between criteria. It should be noted that there is no interaction between criteria in the case of preference independence (see, *e.g.*, Keeney and Raiffa, 1976). The possible weakening of preference independence, implying some form of interaction between criteria, has been under discussion for some time (see, *e.g.*, Fishburn and Keeney, 1975; Keeney, 1981). Probably the most well-known method emerging from this literature is the multilinear utility functions (Keeney and Raiffa, 1976). This method aggregates values of the considered criteria through a weighted-sum of products of the marginal utilities corresponding to the single criterion over all the subsets of criteria. The limitations of this aggregation procedure are the difficulty in defining the many, and to some extent heterogeneous, weights (one for each subset of criteria) and the marginal utility functions themselves. Another methodology to deal with interaction among and between criteria considers non-additive integrals, such as the Choquet integral (Choquet, 1953; Grabisch, 1996) and the Sugeno integral (Sugeno, 1974) and their generalization, such as the bipolar Choquet integral (Grabisch and Labreuche, 2005) or the level dependent Choquet integral (Greco et al., 2011). The basic idea of this approach is that the interaction between criteria can be modeled through the non-additive importance of criteria represented by the value assigned to each subset of criteria by a capacity, called also a fuzzy measure. This is valid at least in the basic version of the Choquet integral and Sugeno integral. This approach has several drawbacks (see Roy, 2009), the most important of which is that they require evaluations on criteria expressed on the same scale (for a proposal to determine the common scale that is necessary in order to apply the Choquet integral, see Angilella et al., 2015). Recently, the interaction between criteria through a weakening of the preference independence condition has been given some consideration in the domain of Artificial Intelligence through GAI-networks (Gonzales and Perny, 2004), as well as UCP-networks (Boutilier et al., 2001), which are based on the idea of Generalized Additive Independence (GAI) decomposition introduced by Fishburn (1970). They allow for aggregating performances on the considered criteria through the sum of marginal utilities related to subsets of criteria. The main problem with these methods is the difficulty in eliciting the marginal utilities from preference information given by the decision maker. Another approach, recently proposed to deal with the interaction of criteria, is the use of enriched additive value functions. Besides the usual sum of marginal utility functions related to each of the considered criteria, these have some further terms representing interaction between a small number of couples of criteria in terms of bonus, in the case of synergy between criteria, or penalization, in the case of redundancy between criteria (Greco et al., 2014). Since the decision-maker could have some difficulties in defining for which couples there is synergy or redundancy, the couples of interacting criteria are singled out with an ordinal regression approach on the basis of some preference information expressed by the decision-maker in terms of pairwise preference comparison of alternatives. Another possibility, recently proposed in the literature (Corrente et al., 2014), is to apply a Choquet-like aggregation method in aggregation of the preference functions outranking methods apart from Electre methods, such as the Promethee methods.

Taking into account all the above aggregation procedures, the choice of an extension of Electre III taking into account interactions between criteria (Figueira et al., 2009) was judged to be completely adequate for dealing with the case study presented in the next section, for the following reasons:

(*i*) Electre methods allow for dealing with heterogeneous scales. In the present study the performances of the actions were expressed on ordinal scales for four criteria, while for the other two criteria the scales were quantitative.

(*ii*) Electre methods are able to take into account purely ordinal scales, thus maintaining their original concrete verbal meaning. In other words, there is no need to convert the original scales into abstract ones with an arbitrary imposed unit and range.

(*iii*) Electre methods also allow for taking into account indifference and preference thresholds when modeling imperfect knowledge of data. In our study it was necessary to take imperfect knowledge into account; for such a purpose the definition of indifference and preference thresholds seemed perfectly adequate.

(*iv*) The generalization of Electre methods allows for consideration of the interaction between some couples of criteria, which seemed to be present in our study. In addition, it was considered to be the right opportunity for testing the applicability of Electre III with interactions.

3. Case study: The requalification of an abandoned quarry

This study deals with the characterization and comparison of alternative projects for the requalification of an abandoned quarry located in Northern Italy. In particular, this study concerns the analysis and the comparison of five projects in order to rank them from the best to the worst one. Details about the case study are provided in what follows.

3.1. A brief description of the context

The application performed in the present research is based on the results coming from a previous study where the alternative options have been identified and investigated (Brunetti, 2007; Bottero et al., 2014). The area under analysis refers to a quarry that has been abandoned since 1975 and covers a total surface of 65 000 m^2, with a depth of approximately 25 m from the ground level. Due to its abandoned state the area is now characterized by uncontrolled vegetation growth and by water-filled pits. Furthermore, the area under analysis is part of the Provincial ecological system of environmentally valuable sites.

For the reclamation of the area five alternative projects have been considered, that can be described as follows: 1) basic reclamation, 2) to plant a forest, 3) development of a wetland, 4) implementation of the ecological network, and 5) construction of a recreational structure. It is worth mentioning that the projects represent real projects, which are now under investigation from the Municipal Authority for the transformation of the area. The five alternative options that were proposed for the requalification of the abandoned quarry can be described in a more detailed forma as follows:

1. *Basic reclamation*: This alternative involves the filling of the quarry, the implementation of security measures on the quarry' slope characterized by landslide risk, the laying of the topsoil, the natural evolution of the vegetation, and the accelerated growth of the autochthonous black locust wood.
2. *Valuable forest*: This alternative involves the filling of the quarry, the implementation of security measures on the quarry' slope characterized by landslide risk, the laying of the topsoil, the cover with drainage material, and the establishment of an oak-hornbeam wood.
3. *Wetland*: This alternative involves the partial filling of the quarry, the implementation of security measures on the quarry' slope characterized by landslide risk, the surface sealing, the creation of a lake, the planting of wetland vegetation, and the natural evolution of the surrounding wood and of the wetland.
4. *Ecological network*: This alternative consists of the partial filling of the quarry, the implementation of security measures on the quarry' slope characterized by landslide risk, the surface sealing, the realization of lakes, pedestrian and equestrian pathways, and recreational areas, the predisposition of information and educational material, and the natural evolution of the existing wood.
5. *Multi-functional area*: This alternative involves the partial filling of the quarry, the implementation of security measures on the quarry' slope characterized by landslide risk, and the construction of sports and residential structures that are completely self-sufficient in terms of energy and waste water disposal and that are harmoniously integrated with the landscape.

3.2. Stakeholders: Their concerns, values, and expectations

One crucial point of a decision process consists of the identification and classification of the stakeholder groups (entities), which can be defined as those who can affect the realization of organizational goals or group of individuals affected by the realization of the organizational goals. It has been recognized that mapping the stakeholders allows the comprehension of fundamental issues, such as the level of interest of each stakeholder group to impress its expectations on the project decisions and the powerful of each group of affecting the project decisions. In the present analysis, the environmental planning and management involve different stakeholders with conflicting objectives and interests. It would thus be necessary to consider the opinions of all the stakeholders for a sound decision aiding process.

Table 1 surveys the relevant stakeholders which can have a role in the process. The stakeholders are all the individuals or entities/institutions which are related to the use and/or the management of the area, including the Regional Authority, the Provincial Authority, the Regional Environmental Authority, the Forestry Corp, the Municipal Technical Office, the Mayor, the local practitioners, the inhabitants, and the private entrepreneurs. This structure comprises all the involved stakeholders.

Stakeholders	**Level**	**Description**
Forestry Corp	National	The Forestry Corp is a National Police Force in charge for the defense of natural heritage and landscape. In case of deep transformation of the area under investigation, a delegate from the Forestry Corp will take place in the Environmental Impact Assessment procedure.
Regional Authority	Regional	The Regional Authority is in charge for the territorial and landscape planning and for the environmental management. In this case, if the project will require a modification of the Municipal Plan, the Regional Authority will have to approve the change. Furthermore, the Landscape Regional Plan identifies the area as valuable from a landscape point of view.
Regional Environmental Authority	Provincial	The Provincial Authority is responsible for the territorial and landscape planning and for the environmental management at the provincial level. The interests in the case under examination are related to the fact that the area is part of the Provincial Ecological Network that links many territorial areas of particular importance from a naturalistic point of view. Moreover, the Provincial Authority is in charge for controlling all the operations related to mining activities (opening of new activities, exercise, closure and environmental rehabilitation).
Municipal Technical Office	Local	The Municipal Technical Office is in charge for controlling all the construction activities. In this case, it will evaluate the transformation project in order to verify if it complies with the legislation.

Mayor	Local	The Mayor is the chief of the Municipality and has the responsibility of approving or rejecting the transformation project. The interests are related above all to ensure the quality of life of the local population and to grant the financial-economic stability of the Municipal Authority.
Local practitioners	Local	They represent the practitioners having a bureau in the zone under analysis and working in the field of architecture, urban planning and agronomy. They could be involved in the transformation project for the area.
Inhabitants	Local	The local population could be affected by the transformation project. Their interests are related to preserve the environmental system and to increase the level of services in the area.
Private entrepreneurs	Local	They represent the private bodies that might be interested in investing money in the transformation project that considers the construction of a multi-functional area.

Table 1: Survey of the most relevant stakeholder groups

3.3. Building a coherent family of criteria

This subsection is devoted to the construction of the family of criteria, the identification of projects and their performances, as well as the definition of the discriminating thresholds associated with criteria (see Appendix *A*).

3.3.1. Criteria

Starting from the overall objective of the analysis, which is the identification of the most sustainable ranking of the projects for the reuse of the abandoned quarry, a coherent set or family of criteria that reflects all the concerns relevant to the decision problem has been identified, paying attention to their exhaustiveness, cohesiveness, and non-redundancy (Roy and Bouyssou, 1993). The criteria considered in the present application were selected based on the relevant international literature (Bascetin, 2007; Rey-Valette et al., 2007; Golestanifar and Bazzazi, 2010; Soltanmohammadi et al., 2010) and on the requirements coming from the legislative framework in the context of Environmental Impact Assessment (first of all, the European Directive 2014/52/EU). In order to find the most suitable project for the reuse of the abandoned quarry, a family of six criteria has been built (Table 2). Both, quantitative and qualitative criteria, have been used for the analysis.

Criteria	**Unit**	**Description**
Investment costs	Euros	This criterion models the construction costs [min].
Profitability	Qualitative judgment	This criterion refers to the financial efficacy of the investment and to the consequences that the project may determine on the local economic system in terms of public revenues [max].

New services for the population	Qualitative judgment	This criterion models the availability of new services for the population, such as green areas, recreational areas, sports structures, etc. [max].
Landscape ecology	*ha*	This criterion models the effects of the project on the landscape quality, on bio-diversity conservation and on the local ecological network, in terms of hectares of naturalized area [max].
Environmental effects	Qualitative judgment	This criterion models the effects that the project is likely to produce on the physical environment (hydrology, geo-technical conditions, etc.) [max].
Consistency with the local planning requirements	Yes/No	This criterion models the presence of constraints that could affect the transformation project and to the consistency with the planning instruments in force [max].

Table 2: Description of the considered criteria

Two of the co-authors os this paper (M. Bottero and V. Ferretti) are very familiar with problems in the domain of sustainable assessment. They had good reasons to think that we should not discard *a priori* the possibility of the existence of interactions between some pairs of criteria (*cf.* Section 1). The work performed in this paper (*cf.* Section 4) shows that they were right.

3.3.2. Performances table

Table 3 presents the performances of the five projects $\{a_1,\ a_2,\ a_3,\ a_4,\ a_5\}$ according to the six considered criteria. The criteria "profitability", "new services for the population", and "environmental effects" are expressed on the following seven-level qualitative scale: very bad (1), bad (2), rather bad (3), average (4), rather good (5), good (6), very good (7). This is a numerical but ordinal scale, used for encoding the original verbal scale. It is useful only to work with figures instead of the verbal statements; these figures are simply the rank of the verbal statements.

	Investment (g_1)	Profitability (g_2)	Services (g_3)	Landscape (g_4)	Environment (g_5)	Consistency (g_6)
a_1	30 000	rather bad (3)	very bad (1)	2	average (4)	yes (1)
a_2	45 000	rather bad (3)	rather good (5)	5	rather good (5)	yes (1)
a_3	90 000	very bad (1)	good (6)	3.2	very good (7)	yes (1)
a_4	120 000	very bad (1)	very good (7)	3.5	good (6)	yes (1)
a_5	900 000	very good (7)	very good (7)	1	rather bad (3)	no (0)
q_j	15 000	1	1	0.5	1	0
p_j	20 000	1	1	1	1	0

Table 3: Performances table with discriminating threshold values

3.3.3. Thresholds

To take into account the imperfect character of data, ELECTRE methods make use of discriminating (indifference and preference) thresholds (see subsection $A.2$). Table 3 thus presents also the discriminating thresholds (indifference, q, and preference, p) identified for the six criteria. In particular:

- For the qualitative criteria ("profitability", "new services for the population", and "environmental effects") the indifference thresholds and the preference thresholds are both equal to 1; this means that two performances which are put on two consecutive levels on the qualitative scale cannot be considered as significantly different (these values have not a quantitative meaning, for more details see Roy et al. 2014);
- For the criterion "consistency with the local planning requirements", there are no thresholds (both are equal to 0).
- For the quantitative criteria ("investment costs" and "landscape ecology") the indifference threshold could not be 0 and the preference threshold had to be strictly higher than the indifference threshold. In particular, for the criterion "investment costs" a difference bigger than 20 000 Euros means that the cheaper alternative is strictly preferred and a difference of 15 000 Euros is compatible with an indifference between the two alternatives. As for the criterion "landscape ecology" the indifference threshold was fixed at 0.5 *ha* while the preference threshold at 1 *ha*.

3.4. Why to constitute a focus group?

The implementation of ELECTRE III with interaction between criteria requires the specification of the role it is suitable the different criteria must play as well as the nature of the interactions which may exist between these criteria. This is performed by assigning numerical values and indetermination margins to several parameters. For such a purpose, the analyst considered appropriate to form a panel of experts working together, side-by-side, through the application of a focus group technique (see, for instance, Morgan, 1988; Morgan and Krueger, 1993; Stewart and Shamdasani, 1990). These experts should be able to take into account the points of view of the different stakeholders. Indeed, in the present application, a close attention was devoted to the formation of a group of experts having a balanced background composition. For this reason, an expert in the field of economic evaluation, an environmental engineer, and an expert in landscape ecology constitute this focus group.

4. Presentation of the work with the focus group

The work by the focus group has been organized in three major phases according to the following structure. In a first phase (say, a learning phase), the analyst promoted an individual discussion with each expert for reflecting and thinking about the relative importance of criteria, and then, built a set of weights for each one of the three experts, separately. In a second phase, the main task of the analyst was devoted to promote a discussion about the sets of weights obtained in the previous phase, and then, help in building a consensual set of weights for the group. Finally, in the third phase, the analyst led the experts to discuss and work side-by-side about the nature of the interactions which may exist between criteria and about the way of taking into account such interactions. Each one of these three phases will make the object of one of the following three subsections. Let us underline that in what follows it is not a matter of veto thresholds. The analyst explained to the experts what a *veto* effect consisted in. The experts thought that, considering the nature of the case under study, there was no reason to assign a *veto* power to any of the six considered criteria.

4.1. Phase 1 (learning): construction of a set of individual weights

Indeed, this first phase is a learning phase, which is intended to make the notion of the relative importance of the different criteria understandable for the three experts. These experts worked separately, the object being to give the possibility to each one of the three experts to explain the way they wanted to differentiate the role every criterion must play, according to the opinion of each one of them. With such a purpose in mind, the analyst used the SRF (Simos-Roy-Figueira) method for helping and assisting the experts.

This stage started with a collective presentation of the way this method (Figueira and Roy, 2002) should be able to help the experts to express their judgments with respect to the relative importance of criteria.

1. The analyst gave to every expert a deck (pack, or set) containing six cards with the front of each card carrying the name (or a label) of every criterion that distinguish it from the other cards in the deck; the analyst also gave them a big enough number of blank cards; the purpose of such blank cards being explained to the experts by the analyst slightly later on in the interaction protocol.
2. The analyst asked every expert to regroup cards corresponding to criteria of the same weight in order to constitute, if necessary, packets of ties (the analyst said to them that these packets will be, most often, reduced to the a single card, what was definitely the case here for every one of the three experts and for all the six criteria).
3. Then, the analyst asked every expert to rank (or line up) the tied packets by an increasing order of their weights, by explaining them that the least important packet will be assigned to the rank 1, the second least important to the rank 2, and so on.
4. The analyst also called the attention of every expert to think about the fact that two successive tidying up packets of criteria in the ranking can have, according to their opinion, a more or less close importance; after the expert have been reflecting about this more or less close importance, the analyst asked him to materialize it by inserting blank cards in between the successive packets of criteria; the analyst finally explained to each expert that, no blank card means that both packets will not have the same weights, but the difference in the weights would be minimal; only one blank card means twice the minimal difference when compared to the absence of blank cards; two blank cards correspond to three times the minimal difference, and so on.

Table 4 contains the information obtained from every expert when applying the procedure above.

Experts	r_1	n_1	r_2	n_2	r_3	n_3	r_4	n_4	r_5	n_5	r_6	N
E_1: Economic Evaluation	g_6	2	g_4	0	g_3	0	g_1	0	g_2	0	g_5	2
E_2: Environmental Engineering	g_6	2	g_3	2	g_2	1	g_4	3	g_1	2	g_5	10
E_3: Landscape Ecology	g_6	1	g_2	1	g_1	3	g_3	2	g_4	2	g_5	9

Table 4: Ranking of criteria and blank cards for the three experts (where, g_1 = "investment costs", g_2 = "profitability", g_3 = "services", g_4 = "landscape", g_5 = "environmental", and g_6 = "consistency"; r_j, represents the position of criterion j, for $j = 1, \ldots, 6$; n_j, is the number of blank cards between positions j and $j+1$ in the ranking of criteria, for $j = 1, \ldots, 5$; and, N is the overall number of blank cards for each expert).

The analyst was not surprised to obtain different rankings since the three experts have a very different background and, as a result, their approach in the analysis of problem is also very different.

At this point, the analyst explained to the experts that in order to assign the numerical values to the weights, which must reflect the relative importance of criteria according to the preference information they provided (*cf.* Table 4), they need to answer an additional question. The analyst, therefore, asked, every expert, that he should tell how many times the last packet of criteria (that is to say, the most important) is more important than the first one (this ratio will be denoted by Z). Finally, the analyst specified to every expert that he have three possible alternatives to define this value: a single very definite value, a range, or three distinct values (a minimum, a maximum, and a central value).

The obtained answers, as well as the weights that result from such answers by applying SRF, are provided in Table 5.

Experts	Z	w_1	w_2	w_3	w_4	w_5	w_6
E_1: Economic Evaluation	7	19.3	22.4	16.2	13.0	25.5	3.6
E_2: Environmental Engineering	15	25.9	14.0	8.1	18.0	31.9	2.1
E_3: Landscape Ecology	14	11.2	6.8	20.0	26.5	33.1	2.4

Table 5: Normalized weights for each criterion and for each expert.

The reader will note that one of the experts gave to Z a very different value (7) of those given by the two other experts (15 and 14). The analyst wanted to know the impact on the set of weights provided by SRF of these differences. For this purpose, the analyst applied SRF to the preference information provided by the first expert, but with different values for the ratio Z (see Table 6).

E_1: **Expert in Economic Evaluation**	w_1	w_2	w_3	w_4	w_5	w_6
$\mathbf{Z = 7}$	**19.3**	**22.4**	**16.2**	**13.0**	**25.5**	**3.6**
$Z = 10$	19.5	22.9	16.1	12.7	26.2	2.6
$Z = 14$	19.6	23.2	16.1	12.5	26.7	1.9
$Z = 15$	19.6	23.2	16.1	12.5	26.8	1.8

Table 6: Normalized weights for the Expert in economic evaluation according to different values for the ratio Z.

4.2. Phase 2: construction of a common set of weights

The analyst began by calling the attention of the experts to the convergence or agreement points. This is essentially related to the position (see Table 4) of criterion g_6 (services), as being the least important, and the position of criterion $g5$ (effects), as being the most important one. Then, the analyst especially stressed the divergences. First, the analyst pointed out that the expert in economic evaluation inserted very few blank cards (only 2, while the other experts inserted 9 or 10). This led to a more narrowed set of weights with the value 7 he assigned to the ratio Z, instead of 14 and 15 (*i.e.*, the values given by the two other experts). Then, the analyst called the attention of the experts to the very major divergence (*cf.* again Table 4). This disagreement is related to the relative position in the ranking of criteria g_1 (investment costs) and g_2 (profitability). The expert in economic evaluation assigned the two criteria, respectively, to ranks 4 and 5, while the two other experts reversed their respective ranks: the expert in environmental engineering puts them, respectively, in ranks 5 and 3, and the expert in landscape ecology gave them, respectively, ranks 3 and 2. Besides, if they take into account the place of blank cards, it clearly appears that these two experts wanted to assign a distinctly less important role to criterion g_2, than the role the expert on economic evaluation wanted to give to this same criterion (this is what Table 5 clearly shows).

These divergences led to some exchanges between the expert in economic evaluation and the two others. By means of several explanations, the three experts shared their opinions. These explanations led them to re-examine the role which they agreed to want to play certain criteria, especially concerning the ranking of the most distant criteria from their domains of expertise.

For instance, the economic evaluation expert succeeded in making understandable for the two other experts the fact that profitability (g_2) is much more important than investment costs (g_1). He explained that the investment costs in a new project is not very important; indeed, what is really important is the fact that this project can generate important incomes (therefore, a high profitability) in order to remunerate the costs of an intervention (that is, the investment costs). The experts in landscape ecology and in environmental engineering, therefore, saw again how they ranked the criteria and they decided to put profitability (g_2) with a higher importance than the investment costs (g_1) (while in the first phase of the interaction process the situation was the opposite). Finally, the debate converged to a new ranking:

$$g_6 \prec g_3 \prec g_1 \prec g_4 \prec g_2 \prec g_5,$$

where $\prec$ means “strictly less important than”. See also Table 7.

	r_1	n_1	r_2	n_2	r_3	n_3	r_4	n_4	r_5	n_5	r_6	N
Group of the three experts	g_6	2	g_3	3	g_1	1	g_4	3	g_2	2	g_5	11

Table 7: Common ranking of criteria and blank cards for the group of experts.

Concerning the value of Z, an agreement was achieved around the value 16. It appeared interesting to the analyst to see also the impact which would have the ratios 14 and 15 (*cf.* Table 8 below).

Group of the three experts	w_1	w_2	w_3	w_4	w_5	w_6
$Z = 14$	14.9	25.7	7.6	18.5	31.1	2.2
$Z = 15$	14.8	25.8	7.5	18.5	31.3	2.1
$\mathbf{Z = 16}$	**14.8**	**25.9**	**7.5**	**18.5**	**31.3**	**2.0**

Table 8: Normalized weights for the group of three experts according to different values for the ratio Z.

The participants found that the work done by the focus group was a very interesting task. The SRF methodology for the determination of weights was very well accepted and it has been considered useful for reflecting the respective role played by the different criteria involved in this study. The discussion raised by the comparison of the three rankings of the cards, proposed in the first phase by the experts working separately, made it possible to realize that the interpretation of the meaning of the criteria was not the same for the three experts. Once this meaning was clarified and unified, the manipulation of the cards-criteria and the visualization of the way they were ranked led quite quickly to an agreement about the respective role the different criteria should play in the decision aiding process. Finally, the assignment of a value for the ratio Z gave rise to some debates, but the experts easily came to an agreement on the value $Z = 16$. As for the choice of the previous value, the agreement about the choice of the values since $Z = 14$ or $Z = 15$ was also easy to reach, leading to three sets of non significantly different weights (*cf* Table 8).

4.3. Phase 3: details of the implementation on how to take into account the interaction between criteria

The analyst organized this phase in three steps: the first one consisted of an explanation about what every type of interaction effect could take into account; the second was devoted to an inventory of the type of interactions to be taken into account; and the third dealt with the manner of taking the interactions into account.

4.3.1. First Step

The analyst explained to the experts the nature of the interactions between criteria that Electre method allows to take into account. For such a purpose, the analyst made use of two examples, the first related to the project of building a new hotel, and the second concerning the purchase of a new digital camera, such as they were introduced in Figueira et al. (2009). On the one hand, the three experts had no difficulty to understand the effects of mutual-strengthening and mutual-weakening. On the other hand, additional explanations were necessary for rendering well understandable the antagonistic effect.

The experts raised the following question: "by analyzing the interactions, should we think about what is going on in the general case of a problem of land-use planning, or must we consider directly the particular case in which we are interested in here?" The analyst recommended the experts to begin by considering the general case, and then examine if their conclusions remain valid for the particular case. In territory land-use planning problems, it is actually possible that certain interaction effects will depend on the particular case under analysis. The experts presented, as an example, an environmental noisy pollution case. The importance of this impact can strongly depend on the morpho-geological characteristics of the territory where the impact will take place. If the impact is produced by a road crossing a village, this impact will be considered in a negative manner, when compared with a case were the road passes in a place where nobody lives in. In a more general way, it is therefore necessary to consider that the decision-aiding problems in an environmental domain must be dealt with by taking into account all the particular features of the site being analyzed.

4.3.2. Second Step

To prepare the experts for this systematic exam, the analyst wished to begin by making them reflect on three different cases of interaction between criteria (one with all the types of effects), which the analyst judged (considering their knowledge on the concrete case) justified to keep for analysis. Indeed, it is important the reader can understand in which purpose the three cases were proposed to begin the discussion with the experts.

A possible strengthening effect between criteria g_1 (investment costs) and g_2 (profitability). "Should not we consider that from the very moment a project a brings more benefits than a project a', being project a less costly, the way these two criteria give their contribution to the credibility of the outranking aSa' must be more significant than the way we obtain by the simple addition of the two impacts related to each one of these criteria when only one validates the assertion 'a is at least as good as a''?" The analyst justified the *raison d'être* of such a strengthening effect by emphasizing that a project of high cost will normally have a high profitability too. The expert gave the following example: luxurious houses which are very expensive to construct (due to the high quality of materials, sophistication of the thermal and electrical installations, and so on) are normally sold at a very high price, but with a very high profitability too. This argument did not persuade the experts. It does not seem for them to be relevant and appropriate in the considered case, which is related to a project of public interest. In this type of projects, the very large expenses are accompanied, in general, by a rather low profitability (it is, for example, the case of the construction of a public park). It does not seem adequate to the experts, therefore, to be justified to take into account a form of synergy (or mutual-strengthening) between the two criteria, investment costs (g_1) and profitability (g_2).

A possible weakening effect between criteria g_4 (landscape ecology) and g_5 (environmental effects). "Should not we consider that from the very moment a project a is at least as good as a project a', on each one of the two criteria, the way these two criteria give their contribution to the credibility of the outranking aSa' must be less significant than the way we obtain by the simple addition of the two impacts related to each one of these criteria when only one validates the assertion 'a is at least as good as a''?" The experts recognized that this weakening effect was worth being kept. Indeed, it seems to them that it is very probable that if a project is characterized by a good performance in terms of landscape ecology it will also have a good performance in terms of environmental effects. Consequently, the joint impact of these two criteria must be less than the sum of the impacts which they have when they intervene separately.

Possible antagonism of criterion g_5 (environmental effects) over criterion g_2 (profitability). "Should not we consider that from the very moment a project a is at least as good as a project a', on criterion g_2 (profitability), but a' is significantly preferred to a on criterion g_5 (environmental effects), the way criterion g_2 gives its contribution to the credibility of the outranking aSa' must be less significant than the way we obtain when criterion g_5 does not validate the assertion 'a' is significantly preferred to a'?" The experts have considered that this antagonism was worth being kept. According to them, if a project (for instance, a_1, see Table 3) has a so good profitability when compared to another project (for instance, a_3, see again Table 3), while the respective performances of these two projects on criterion g_5 (environmental effects) lead to make clear an opposition to the outranking of the second project by the first (a_1Sa_3), the contribution of criterion g_2 to the credibility of this outranking must really be less than the weight of this criterion, w_2. To justify this position, the experts make a reference to real-world cases as well as to the scientific literature about studies on environmental impacts. Indeed, these studies showed that when a project has less environmental benefits than another one (as a_3 with respect to a_1), the benefits which come from the profitability are partly hidden by the least good environmental performance. The reduction on the weights of the criterion profitability, in the computation of the credibility of the considered outranking (for instance, a_1Sa_3), appeared to them as an adequate way of taking into account the effect of which it has just been a matter.

The examination of the twelve other cases of possible interaction led the experts to keep a case of mutual-strengthening and a second case of antagonism, as illustrated in the following paragraphs.

Strengthening effect between criteria g_1 (investment costs) and g_5 (environmental effects). The experts justified this interaction effect as follows. A project which is characterized by weak environmental effects has all the chances to be also characterized by low intervention costs (investment costs). This leads to consider that a project where the investment costs are low, but that, however, has good environmental effects is worth being very well appreciated. This effect can be taken into account by assigning to criteria g_1 and g_5, when they contribute conjointly to validate an outranking, an overall weight greater than the algebraic addition of the weights w_1 and w_5, which they have when they intervene separately to validate this outranking.

Antagonism of criterion g_4 (ecology) over criterion g_2 (profitability). The arguments to keep this interaction effect are similar to the ones leading to keep the antagonism suggested by the analyst (antagonism of g_5 against or over g_2).

4.3.3. Third Step

Having identified the four cases of interaction, which was worth being kept, the analyst must now to get the experts to work together about the way of taking into account these four cases. For such a purpose, the analyst must have asked the experts to assign a numerical value to the interaction coefficients k_{ji} and k'_{hj} as they were defined in subsection A.3.2. This was made through a dialogue between the analyst and the experts as we shortly present in what follows.

a) "You have considered that it was necessary to take into account a strengthening effect between criteria g_1 (investment costs, weight $w_1 = 14.8$) and g_5 (environmental effects, weight $w_5 = 31.3$). This strengthening effect intervenes when both criteria g_1 and g_5 conjointly contribute to validate the assertion 'a outranks a''. To take into account this strengthening effect, it is needed, under these conditions, to assign to the coalition of both criteria (investment costs, environmental effects) a weight greater than the sum $w_1 + w_5 = 14.8 + 31.3 = 46.1$. What is, under these conditions, the value which it is necessary, according to you, to assign to the weight of this coalition?" The experts felt difficulties to answer this question. They understood perfectly the sense of the question, but they did not know on which foundations to take support to provide a ciphered answer. They asked if the analyst could provide an interval (a minimum and a maximum) in which they should place the asked value. First of all, the analyst pointed out that, in the case of a strengthening effect considered extremely weak (in other words, negligible) a minimum value was 46.1. Then, in the case of a strengthening effect judged extremely strong, the analyst offered a suggestion (as an example) that the maximum could be the double, that is, the value 92.2. On these foundations, the experts came to an agreement, to assign a weight of 60 to the coalition of both criteria g_1 and g_5, when they intervene conjointly. It follows that the value of the strengthening coefficient k_{15} is: $60 - 46.1 = 13.9$, rounded up to 14.

b) "You have considered that it was necessary to take into account a weakening effect between criteria g_4 (ecology, weight $w_4 = 18.5$) and g_5 (environmental effects, weight $w_5 = 31.3$). This weakening effect intervenes when both criteria g_4 and g_5 jointly contribute to validate the assertion 'a outranks a''. To take into account this effect, it is needed, under these conditions, to assign to the coalition of both criteria (ecology and environmental effects) a weight lower than the sum $w_4 + w_5 = 18.5 + 31.3 = 49.8$. What is, under these conditions, the value which it is necessary, according to you, to assign to the weight of this coalition?" Again, the experts asked the analyst to propose them an interval in which they should place the asked value. First of all, the analyst pointed out that a weakening effect could lead at most to the weight the most important criterion weight must contribute by itself only to the credibility of the outranking (the other criterion bringing no additional information). It follows that an adequate minimum value is 31.3 (maximum weakening). In the case of a weakening effect, considered extremely weak (in other words, considered negligible), the weight of the coalition could stay, under these conditions, equal to $w_4 + w_5 = 49.8$. On these foundations, the experts came to an agreement to assign a weight slightly greater than 40 (40.8) to the coalition of both criteria, g_4 and g_5, when they intervene conjointly. It follows that the value of weakening coefficient k_{45} is $40.8 - 49.8 = -9$.

c) "You have considered that it was necessary to take into account an antagonism of criterion g_4 (ecology) over criterion g_2 (profitability, weight $w_2 = 25.9$). This antagonism intervenes when a project 'a is at least as good as a project a'' on criterion g_2, while a' is significantly preferred to a on criterion g_4. To take into account this antagonism, it is needed, under these conditions, to assign to the criterion g_2 (profitability) a weight lower than or equal to $w_2 = 25.9$. What is, in these conditions, the value which it is necessary, according to you, to assign to the weight of this criterion?". The analyst still offered an interval here, and started again to pointing out that if the antagonism is extremely weak (in other words, negligible) an adequate maximum value is $w_2 = 25.9$. In the case of an antagonism judged extremely strong, the analyst suggested to suppose (as an example) that the minimum value could be the half of the weight w_2, that is to say, 13. The experts had a little more difficulties here than in both of the precedent cases to agree about a value. It is finally the value 20 which was kept. It follows that the value of the antagonism coefficient k'_{24} is $25.9 - 20 = 5.9$, rounded up to 6.

d) The experts considered that the antagonism of criterion g_5 (environmental effects) over criterion g_2 (profitability) was of the same nature and also of the same importance as the antagonism of g_4 (ecology) over criterion g_2. It led to put $k'_{25} = 6$.

Table 9 sums up the results gathered in this third step.

	Investment (g_1)	Profitability (g_2)	Services (g_3)	Landscape (g_4)	Environment (g_5)	Consistency (g_6)
Investment (g_1)					$k_{15} = 14$	
Profitability (g_2)				$k'_{24} = 6$	$k'_{25} = 6$	
Services (g_3)						
Landscape (g_4)					$k_{45} = -9$	
Environment (g_5)	$k_{51} = 14$			$k_{54} = -9$		
Consistency (g_6)						

Table 9: Interaction coefficients (this table contains all necessary unambiguously information for interactions: the absence of figures characterizes the absence of interactions; the presence of a figure repeated in a symmetrical manner with respect to the main diagonal characterizes a strengthening effect if the figure is positive and a weakening effect if the figure is negative; the presence of a figure appearing only above or under the main diagonal, in other words not repeated in a symmetrical manner, characterizes an antagonism).

The analyst checked if the positive net balance condition (now with the normalized weights and interaction coefficients) was fulfilled for the common set of weights. It is related to the criteria g_2, g_4 and g_5:

$$w_2 - k'_{24} - k'_{25} = 25.9 - 6 - 6 = 13.9 > 0$$
$$w_4 + k_{45} = 18.5 - 9 = 9.5 > 0$$
$$w_5 + k_{54} = 31.3 - 9 = 22.3 > 0$$

At the end of the meeting, the analyst discussed with the experts about the difficulties they felt when assigning numerical values to the interaction coefficients. The analyst asked the experts the following question: "It would have been easier for you, rather than to answer by a numerical value, to make it in a qualitative terms by appreciating the level of interaction on a semantic scale, such as the following one: ⟨*negligible*, *weak*, *medium*, *strong*, *extremely strong*⟩?". Without hesitancy the experts answered in the affirmative. If they like to adopt this mode of questioning, it is naturally necessary to define rules intended to assign numerical values to each one of the levels of interaction characterized in a semantic way. The precedent considerations showed that the rules related to the extreme levels (negligible, extremely strong) depend on the type of the considered interaction effect. Once these minimums and maxima were fixed, we can associate the medium level with the middle of the interval defined by the extreme values, the weak level with the quarter, and the strong level with the three quarters. The resulting values should act then as a basis for a debate with the experts to fix the final numerical value, which it is necessary to adopt.

Despite the difficulties found to assign numerical values to the interaction coefficients, the experts finally agreed to recognize that the way the interactions are taken into account in Electre III were natural and easy to understand. They also understood the manner the numerical values, they had to assign to the interaction coefficients, were used to change the relative importance of the criteria affected by the interaction effects. This seems us to be very positive conclusions in favor of the method within the context of this concrete application. We do not think that similar conclusions would be obtained with methods based on the Choquet integral. The way interactions operate in these methods, through the definition of capacities, seems to us to be much more opaque and, as a result, more difficult to make understandable to the members of a focus group. Finally, let us point out that the antagonistic effect, that turned out to be very appropriate to the land-use planning application considered here, cannot be taken into account with Choquet integral based methods.

5. Sensitivity analysis and robustness concerns

The work with the focus group allows to define a consensual set of weights (*cf.* Table 8, for $Z = 16$) as well as a set of values for the interaction coefficients (*cf.* Table 9). The values of the parameters, which appear in these two tables, determine the role of the different criteria the members of the focus group want to make use for ranking the five projects under analysis. These values were decided following arbitrage and hesitations in order to remove ambiguities which must be taken into account to obtain robust conclusions (*cf.* Section 6). The biggest difficulties which were felt by the members of the focus group concerned the assignment of values to the interaction coefficients. This is why the analyst was interested in an extremely vast set of possible values for such coefficients in order to examine the impact the choice of such a set of values could have on the ranking under analysis. This examination was conducted, in a first phase, with the common set of weights (*cf.* subsection 5.1, below). Then, the analyst tried to verify if the obtained results remained valid with some sets of weights "close" to the common set of weights (*cf.* subsection 5.2, below). Finally, the analyst performed the test with a set of rather different weights (*cf.* subsection 5.3, below). The computational results and experiments presented in this section were performed with a new Q-Basic implementation[1] of Electre III with interactions between criteria.

5.1. Results with the common set of weights: Analysis of the interaction effects

With the common set of weights and in the absence of any interaction between criteria, the application of Electre III leads to the partial pre-order $\mathcal{P}^0$ (see Figure 1a). When taking into account the interaction effects with their original values (*cf.* Table 9) the application of Electre III leads

[1]For more details about this software please ask Salvatore Greco (`salgreco@unict.it`).

to the partial pre-order $\mathcal{P}^1$ (see Figure 1b), which only differs from $\mathcal{P}^0$ for the fact that project a_4 is not any more ranked before project a_1, but it becomes incomparable to the latter.

(a) Pre-order $\mathcal{P}^0$ (b) Pre-order $\mathcal{P}^1$

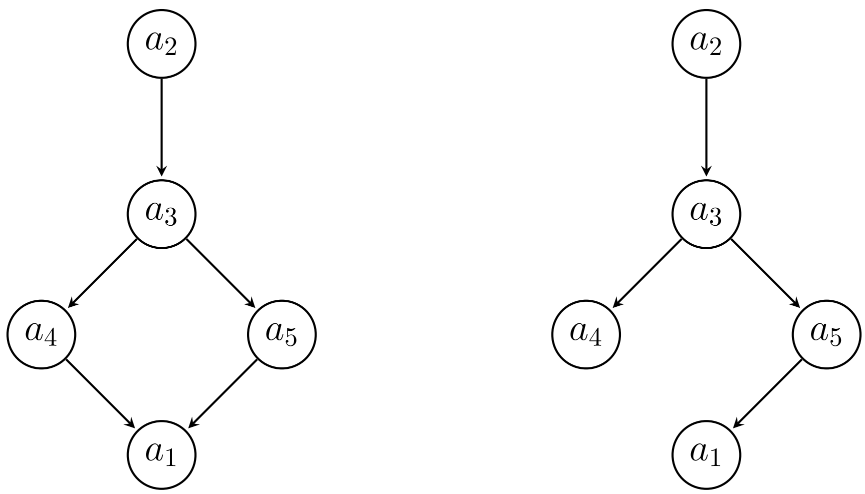

Figure 1: The two obtained pre-orders (rankings)

In a preliminary analysis, the analyst tried to know the partial pre-order to which the application of Electre III leads when only one of the four interaction effects is taken into account. This was done by making the coefficient varying within a range as wide as possible, by taking into account its meaningfulness. Thus, four cases were successively studied.

Case 1: Varying k_{15} *within the range* $[0, 45]$ (values bigger than 45 are considered by the analyst completely unrealistic).

Case 2: Varying k_{45} *within the range* $[-15, 0]$ (the positive net balance condition allows to go until -18.5, but this value was judged by analyst not very realistic since it leads to exclude criterion g_4; this is why the analyst did not considered useful to include values strictly lower than -15).

Case 3: Varying k'_{24} *within the range* $[0, 20]$ (the net positive balance condition allows to go until 25.9, but with this value the antagonistic effect cancels absolutely the role of criterion g_2. The analyst has considered 6 as the minimum weight necessary to keep for criterion g_2 and consequently the limit was 20. This is why 5.9 is the minimum value of the weight, which the analyst considered useful to keep for further analysis).

Case 4: Varying k'_{25} *within the range* $[0, 20]$ (the justification is the same as in the previous Case 3).

In Cases 1, 3, and 4, that is to say, when only, either the mutual-strengthening effect or one of the two antagonistic effects is taken into account, the result is $\mathcal{P}^0$ (see 1a); this occurs for whatever the value of the interaction coefficient within the range under analysis. It highlights that, with the considered set of weights, none of the interaction effects taken separately has an impact in the resulting pre-order.

In Case 2, that is to say, when the mutual-weakening effect is taken into account separately, we find:

- $\mathcal{P}^0$, if the value assigned to the interaction coefficient remains very weak: $|k_{45}| \leqslant 1.333$.
- $\mathcal{P}^1$, for whatever the value of k_{45} within the range $[-15, -1.334]$ (this is the same as in the presence of all interaction effects, with the original values of the interaction coefficients, especially with $k_{45} = -9$).

We shall see in subsection 5.2 the reasons that justify the presence of a critical threshold which leads to switch from $\mathcal{P}^0$ to $\mathcal{P}^1$.

The analyst then wished to see what would happen, on the left and on the right of the critical value -1.333, when the three other interaction effects were active, according to the ranges defined in Cases 1, 3, and 4. The analyst verified that the final result is always $\mathcal{P}^0$ if $|k_{45}| \leqslant 1.333$ and $\mathcal{P}^1$ if $|k_{45}| \geqslant 1.334$.

5.2. Analysis with some sets of weights "close" to the common set of weights

As it has been highlighted in subsection 4.2, after explaining the meaning of each criterion, it was comparatively easy to reach a general consensus about the ranking of criteria by an increasing order of relative importance (*cf.* Table 7). The number of blank cards in each of the inter-criteria spaces previously defined could have led to numbers of blank cards slightly different from those showed in Table 7. That is why the analyst has chosen four other possible dispositions for the blank cards, strongly contrasting with each other, as shown in Table 10. This choice has been done in order to see if with the set of weights obtained from SRF for each of the new dispositions of blank cards the final results would have been different (see Table 11). Therefore, the analyst followed again the same procedure as the one introduced in subsection 5.1 by successively replacing the common set of weights by each one of the four new sets of weights presented in Table 11.

Dispositions	r_1	n_1	r_2	n_2	r_3	n_3	r_4	n_4	r_5	n_5	r_6	N
1	g_6	2	g_3	2	g_1	2	g_4	2	g_2	2	g_5	10
2	g_6	3	g_3	2	g_1	1	g_4	2	g_2	3	g_5	11
3	g_6	3	g_3	1	g_1	3	g_4	1	g_2	3	g_5	11
4	g_6	1	g_3	3	g_1	3	g_4	3	g_2	1	g_5	11

Table 10: Ranking criteria and different dispositions of the blank cards for the group of experts.

In the absence of any interaction, we find the pre-order $\mathcal{P}^0$ for each of four considered sets of weights (as in the case of the common set of weights). When the initial values of the interaction coefficients are kept, especially $k_{45} = -9$, we find (as in the case of the common set of weights) the pre-order $\mathcal{P}^1$ with the sets of weights from dispositions 1 and 2 (*cf.* Table 11). With the sets of weights from dispositions 3 and 4, the resulting pre-order is not any more $\mathcal{P}^1$ but $\mathcal{P}^0$, this shows that the mutual-weakening effect is of no impact with these two new sets of weights. The study of Cases 1, 2, 3, and 4 defined in subsection 5.1 will provide the explanation of this modification.

Dispositions	w_1	w_2	w_3	w_4	w_5	w_6
1	13.7	25.5	7.8	19.6	31.4	2.0
2	14.8	24.0	9.3	18.5	31.4	2.0
3	13.0	24.0	9.3	20.3	31.4	2.0
4	13.0	27.7	5.6	20.3	31.4	2.0

Table 11: Normalized weights for the group of experts with different dispositions of blank cards and $Z = 16$.

In Cases 1, 3, and 4, defined, in subsection 5.1, the obtained results with the four new sets of weights are identical to those obtained with the common set of weights. Moreover, in Case 2 (which takes into account separately the mutual-weakening effect) the critical value, which allows to switch from $\mathcal{P}^0$ to $\mathcal{P}^1$, is -1.333 only when considering the set of weights of Disposition 2: in such a set of weights w_4 has the same value (18.5) as in the common set of weights. With the sets of weights from Disposition 1, w_4 becomes equal to 19.6 and the critical threshold gets the value -8.66; this value characterizes a smaller weakening effect than the one that was characterized by -9. That is why with this new set of weights we still obtain pre-order $\mathcal{P}^1$ when we take into account all the interaction effects with the initial values of the interaction coefficients, especially $k_{45} = -9$. On the contrary, with both sets of weights from Dispositions 3 and 4, w_4 becomes equal to 20.3 and we observe that the critical threshold is at -13.33; a value which characterizes a stronger weakening effect than that characterized by -9. This is why with these two sets of weights we find pre-order $\mathcal{P}^0$ (and not $\mathcal{P}^1$) when all interaction effects intervene with the initial values of the interaction coefficients, especially $k_{45} = -9$.

The previous considerations highlight the coherence of the obtained results. In particular, they make appear the following phenomenon: the higher w_4 the bigger $|k_{45}|$ must be, so that the mutual-weakening effect leads to rank no more project a_4 in a better position than project a_1, but shows instead incomparability between these two projects. Such a phenomenon requires an explanation.

This explanation comes from the fact that the mutual-weakening effect affects the way projects a_4 and a_1 compare to each other (since a_4 is strictly preferred to a_1 according to both criteria g_4 and g_5). We noticed that in the absence of a mutual-weakening effect ($k_{45} = 0$) a_4 is ranked in a better position than a_1. It is not surprising that this ranking disappears to give place to an incomparability when the mutual-weakening effect becomes strong enough to reduce in a significant manner the power criteria g_4 and g_5 have to validate the outranking of a_1 by a_4. This explains the presence of a critical threshold with a value of k_{45}. We must expect that this critical threshold becomes closer to 0 as w_4 decreases, since the credibility of the outranking of project a_1 by a_4 increases when w_4 increases. It is really what we have observed and what it was a matter of an explanation.

5.3. Analysis with the set of weights of expert E_1

The analyst wished to confront the previous results with those that would have been obtained if the set of weights finally kept had been that one of the expert in economic evaluation, E_1. Indeed, it was the expert E_1 (as we saw in subsection 4.2) who contributed to dissipate the poor interpretation of the respective role which it was necessary to attribute to criteria g_1 and g_5. Nevertheless, in the *consensus* resulting from her intervention, it was assigned to criterion g_4 (landscape ecology) a bigger relative importance than that assigned to criteria g_3 (new services) and g_1 (investment costs), while initially, for the expert E_1, it was the opposite situation. Moreover, this expert put very few blank cards between the criteria ranks and assigned the value 7 to the $Z-$ratio. The resulting set of weights from E_1 (*cf.* Table 6) is much more narrowed and rather different from those considered before (*e.g.*, $w_4 = 13$ while previously was $w_4 \geqslant 18.5$).

The analyst, therefore, performed with this new set of weights the same type of computations as those performed with the sets of weights taken in consideration in the two previous subsections. The obtained results are identical, with two very little exceptions. It is worthwhile to present these two exceptions here, even if they will not affect the general conclusions presented in Section 6. It is, finally, also an agreement aspect, which deserves an explanation.

a) On the mutual-strengthening effect

With all the sets of weights studied in subsections 5.1 and 5.2, the result is always $\mathcal{P}^0$ for all the values of k_{15} within the range $[0, 45]$. The mutual-weakening effect thus does not have any impact. With the sets of weights of expert E_1, the result becomes $\mathcal{P}^1$ as soon as k_{15} exceeds 7.99. In other words, from the value 8 and beyond, the result is not any more $\mathcal{P}^0$ but $\mathcal{P}^1$, which means that it is not any more justified to have a_4 better ranked than a_1 since these two projects become incomparable. The reason is the following. First of all, let us point out that the mutual-strengthening effect has no direct impact on the way projects a_4 and a_1 must be compared, since a_4 is strictly preferred to a_1 according to criterion g_5 while it is the opposite with respect to criterion g_1. There is, therefore, an indirect effect, making an influence on the way a_4 compares itself with other projects, that explains the fact that a_4 does not rank in a better position than a_1, when the value of k_{15} exceeds a critical threshold.

For an explanation of this result, let us firstly highlight that in the ranking provided by the descending distillation, a_4 is always placed in a strictly better position than a_1, while in the ranking provided by the ascending distillation, it depends on the considered case, either projects a_1 and a_4 are in the same position, or a_1 is in a better position than a_4. It is this second situation which leads to the incomparability between a_1 and a_4. We saw that this incomparability appeared only with the set of weights of expert E_1 (in which w_4 is weaker than in the common set of weights) and with a strong enough mutual-strengthening effect: $k_{15} \geqslant 0.8$. This is due to the fact that, in the latter case, a_4 is significantly outranked by two other projects, a_2 and a_3, while a_1 is only outranked by one, a_2. In all the other cases, projects a_1 and a_4 are outranked by another single project: a_2 for a_1 and according to the considered case, a_2 or a_3 for a_4.

b) On the mutual-weakening effect

With the considered sets of weights, the mutual-weakening effect has no impact: Either when this effect intervenes separately or when other interaction effects are considered conjointly, the result is still $\mathcal{P}^0$ and never $\mathcal{P}^1$, contrary to the fact that we had observed in subsection 5.2. This change has nothing of surprising. With the sets of weights previously considered, the critical value of $|k_{45}|$ which when exceeded leads to $\mathcal{P}^1$, it was all the more weak than the weight of criterion g_4 was itself weak. With $w_4 = 18.5$ this critical value was at 1.333. In the set of weights considered here, we have $w_4 = 13$. This explains the fact we observe no critical value at all.

c) On the antagonistic effect

In all the studied cases (including those in subsection 5.3) this effect has no impact. We will explain why this effect has no impact, especially in the case of expert E1, but the argument is the same for all the cases. To do so it is necessary to identify all the ordered pairs (a, a') where at least one of the two antagonistic effects could have an impact. It is thus the case if and only if "a outranks

a'" on criterion g_2 and "a' is strictly preferred to a" either on criterion g_4 or on criterion g_5. The analysis of Table 3 leads to the following ordered pairs:

- Antagonism due to criterion g_4: (a_1, a_2), (a_1, a_3), (a_1, a_4), (a_5, a_2), (a_5, a_3), (a_5, a_4).
- Antagonism due to criterion g_5: (a_1, a_3), (a_1, a_4), (a_2, a_3), (a_5, a_2), (a_5, a_3), (a_5, a_4).

For each of these ordered pairs, the credibility of the outranking of a' by a takes into account the weight of criterion g_2. Indeed, the effect of an antagonism contributes to diminish this weight. When in $\mathcal{P}^0$, as well as in $\mathcal{P}^1$, a' is ranked in a better position than a, this reduction of the weight of g_2 (and consequently of the antagonistic effects) cannot produce an impact. We still have to explain why the antagonistic effect has no impact when considering the other three ordered pairs, *i.e.*, (a_1, a_4), (a_5, a_4), and (a_2, a_3).

1. *Ordered pair* (a_1, a_4): The incomparability between these two projects with the set of weights of the expert E_1 does not come from a direct comparison of a_1 against a_4 (the outranking credibility is too weak); it comes instead from indirect effects which take into consideration the way a_4 compares itself with other projects. There is, therefore, no reason why the reduction of the credibility degree of the outranking of a_4 by a_1, following from an antagonistic effect, can lead to a ranking with a1 in a worst position than a_4 (the only effect which could have an antagonism due to criterion g_4).
2. *Ordered pair* (a_5, a_4): In this case an indirect effect influences the way a_4 compares itself with other projects and explains the fact that a_4 is incomparable to a_5, for whatever the considered set of weights. There is, therefore, no reason why the reduction of the credibility degree of the outranking of a_4 by a_5, following from one any of the two antagonistic effects, can lead to a ranking with a_5 in a worst position than a_4.
3. *Ordered pair* (a_2, a_3): Here it is necessary to explain why the antagonistic effect which comes only from g_5 remains compatible with a ranking where a_2 is in a better position than a_3, even with a maximum antagonistic coefficient $k'_{25} = 20$. The value of the credibility degree of the outranking of a_3 by a_2 is equal to:
   - (for the common set of weight): 0.687 in the absence of antagonism and 0.609 with a maximum antagonistic effect.
   - (for the set of weights of expert E_1): 0.745 in the absence of antagonism and 0.681 with maximum antagonistic effect.

These reductions of the credibility degree of the outranking a_3 by a_2 were not sufficient to change the way a_2 and a_3 are ranked.

6. Conclusions

The results presented in Section 5 lead to the following conclusions:

a) In the real case considered in this article the analysis of the results allow us to formulate the following robust conclusions (this term having the sense defined in Roy 2010a,b):

   1. Electre III with interactions between criteria leads to rank a_2 in a better position than a_3, and these two projects in better positions than the remaining three others; this is valid for whatever the considered sets of weights and interaction coefficients. In the same conditions a_5 is ranked in a better position than a_1, and a_4 is incomparable to a_5.

2. Project a_4 is in general ranked in a better position than a_1 by Electre III with interaction between criteria, except when the values for the interaction coefficients k_{15} (mutual-strengthening effect) and/or k_{45} (mutual-weakening effect) exceed a certain critical threshold; in these conditions a_4 becomes incomparable to a_1.

b) These conclusions were obtained following an interactive approach requiring the intervention and interaction with the members of a focus group, that worked together to assign the values of the first sets of weights and interaction coefficients to be introduced in Electre III with interactions for producing the first result. The approach followed to assign such values was easily understood and accepted by the members of the focus group. Uncertainties and ill-determinations which resulted from this approach could be taken into consideration by the method (in particular by using sensitivity analysis) so as to obtain the above introduced conclusions.

c) The results of the previous sections have been introduced to the members of the focus. Their reactions were the following. The first important observation that they made concerned the obtained results. In particular, all the participants confirmed that the two best performing alternatives are coherent with their expectations. A second observation concerned the result of the sensitivity analysis with particular reference to the interaction coefficients. All the participants agreed on the importance of taking into account such interaction effects for environmental decision making processes but suggested that further research should be carried out in order to develop a user friendly protocol for the elicitation of the coefficients.

d) The study of this real case allowed us to test the Electre III method with interactions between criteria to support a public decision related with territorial planning processes. The way the whole work has been developed and conducted, the nature of the obtained results, as well as the way the results were accepted constitutes, in our opinion, a validation of this method for helping to make better decisions in this type of contexts.

A. Appendix: Theoretical and methodological background

This Appendix is devoted to present the fundamentals of Electre III with interaction between criteria. We shall avoid to present some aspects of Electre III, as for instance, the direct and inverse variable thresholds (Roy et al., 2014), and the details of the distillation procedures. For a more complete description of this particular method the reader can refer to Roy and Bouyssou (1993). The family of Electre methods was designed into two main phases. The first one consists of the construction of one or more outranking relations, while the second is related to the exploitation of these relations (Figueira et al., 2005a,b, 2013; Roy, 1985, 1991, 1996). One of the crucial steps of the methodology applied the present work is described in Figueira et al. (2009).

A.1. Basic data

In what follows A denotes a set of *potential actions* or projects, as in our case study. In our settings, each action, $a \in A$, is defined by a brief label, corresponding to an extensive description. In such a case, A can be defined as follows, $A = \{a_1, \ldots, a_i, \ldots a_m\}$. Let g denote a given *criterion*, built for characterizing and comparing potential actions according to a considered point of view. The characterization of an action $a \in A$, denoted by $g(a)$, usually represents the *performance* of action a according to the considered criterion. Let $F = \{g_1, \ldots, g_j, \ldots, g_n\}$ denote a *coherent family of criteria* (Roy, 1985, 1996). The sets A and F contain our basic data. In what follows we shall use also F as the set of criteria subscripts.

A.2. Preference modeling through a pseudo-criterion model

Thresholds are built to take into account the imperfect character of the data from the computation of the performances $g_j(a)$, for all $a \in A$ and $g_j \in F$, as well as the arbitrariness that affects the definition of the criteria.

Definition 1 (Preference threshold)**.** *The preference threshold between two performances, denoted by p, is the smallest performance difference that when exceeded is judged significant of a strict preference in favor of the action having the best performance.*

Definition 2 (Indifference threshold)**.** *The indifference threshold between two performances, denoted by q, is the largest performance difference that is judged compatible with an indifference situation between two actions having different performances.*

The definition of the thresholds allows to define a non-classical model for taking into account the decision-makers preferences.

Definition 3 (Pseudo-criterion with constant thresholds)**.** *A criterion g_j is called a* pseudo-criterion *when two thresholds are associated with g_j: the indifference threshold, q_j, and the preference threshold, p_j, such that $p_j \geqslant q_j \geqslant 0$.*

From the above definitions, the following binary relations can be derived, for each criterion and considering two actions a and a', where $g_j(a) \geqslant g_j(a')$, for a given criterion g_j to be maximized.

1. $|g_j(a) - g_j(a')| \leqslant q_j$ represents a non-significant advantage of one of the two actions over the other, meaning that a is *indifferent* to a' according to g_j, denoted aI_ja'.
2. $g_j(a) - g_j(a') > p_j$ represents a significant advantage of a over a', meaning that a is *strictly preferred* to a' according to g_j, denoted aP_ja'.

3. $q_j < g_j(a) - g_j(a') \leqslant p_j$ represents an ambiguity zone. The advantage of a over a' is a little large to conclude about an indifference between a and a', but this advantage is not enough to conclude about a strict preference in favor of a. This means that there is an hesitation between indifference and strict preference. In such a case, a is *weakly preferred* to a', denoted aQ_ja'.

The following notation about coalitions of criteria will be needed in the remaining of this paper. Let

- $C(aIa')$ denote the subset of criteria such that aI_ja';
- $C(aQa')$ denote the subset of criteria such that aQ_ja';
- $C(aPa')$ denote the subset of criteria such that aP_ja';
- $\overline{C}(a'Pa)$ denote the complements of $C(aPa')$.

A.3. Building an outranking relation

Three concepts are needed to the construction of an outranking relation, namely, concordance, non-discordance, and a degree of credibility. These three concepts will be reviewed in this subsection. The extension of the comprehensive concordance index to incorporate three types of interactions between criteria will be presented in this subsection too.

A.3.1. Concordance, discordance, and credibility

The following three paragraphs will deal with the three main concepts, needed for the construction of a fuzzy outranking relation Roy (1991).

Concordance index. For using Electre III it is necessary to associate a set of intrinsic weights with the family of criteria. This set of weights, each one denoted by w_j, is such that $w_j > 0$, for $j = 1, \ldots, n$, and $\sum_{j=1}^{n} w_j = 1$ (assumption). The overall concordance with the assertion of "a outranks a'" is modeled through a *comprehensive concordance index*, denoted $c(a, a')$, and defined as follows:

$$c(a,a') = \sum_{j \,\in\, C(aPa')} w_j + \sum_{j \,\in\, C(aQa')} w_j + \sum_{j \,\in\, C(aIa')} w_j + \sum_{j \,\in\, C(a'Qa)} w_j \varphi_j, \tag{1}$$

where

$$\varphi_j = \frac{p_j - \big(g_j(a') - g_j(a)\big)}{p_j - q_j} \in [0, 1[. \tag{2}$$

Let us recall that $c(a, a')$ (roughly meaning a degree of outranking of a over a') takes into account the weights of criteria which contribute to validate the assertion, "a is at least as good as a'" denoted by aSa'. Every criterion leading to aPa', aQa', and aIa' is taken into account with its overall weight. It is obvious that a criterion leading to $a'Pa$ must not be taken into account for validating such an assertion. On the contrary, a criterion leading to $a'Qa$ must not be completely discarded with respect to its contribution to the assertion aSa'. This weak preference situation represents a hesitation between $a'Ia$ and $a'Pa$. The criterion is thus taken into account by a fraction, φ, of its weight. This fraction can be interpreted as the proportion of voters (the weight corresponds to the voting power of the criterion) in favor of the assertion aSa'. This proportion should be as close as possible to 1 when the hesitation is more in favor of the indifference. It should be zero when we reach the strict preference situation in favor of a'.

There is a difference that should be pointed out when scales are continuous or when they are discrete (Roy et al., 2014) (for the sake of the simplicity consider the criterion g and the same two actions a and a'):

1. A *continuous scale* leads to the following formula:

$$\varphi = \frac{p - \big(g(a') - g(a)\big)}{p - q}, \quad \text{with} \quad q < g(a') - g(a) \leqslant p, \;\; \text{for} \;\; p \neq q. \tag{3}$$

   This relation leads effectively to:

   (a) $\varphi = 1$ *iff* $g(a') = g(a) + q$: the only situation that validates $a'Ia$ without hesitation.
   (b) $\varphi = 0$ *iff* $g(a') = g(a) + p$: situation that, due to the continuous nature of the scale, only leads to the absence of the hesitation between $a'Ia$ and $a'Pa$; the latter imposes thus its power.

2. When in presence of a *discrete scale* the formula becomes as follows:

$$\varphi = \frac{(p+1) - \big(g(a') - g(a)\big)}{(p+1) - q}, \quad \text{with} \quad q \leqslant g(a') - g(a) \leqslant p, \;\; \text{for} \;\; p \neq q. \tag{4}$$

   It means that in this case we can keep the previous formula (3) by replacing p by $(p+1)$. Let us observe that this formula is still valid when $p = q$, which corresponds to a situation of absence of weak preference. When $p = q + 1$, which corresponds to a unique situation of real hesitation ($g(a') = g(a) + p$), this formula leads to $\varphi = 1/2$ (which seems a very adequate value). Similarly, if $p = q + 2$, each one of the two hesitation situations leads to $\varphi = 2/3$ and $\varphi = 1/3$, respectively.

Discordance index. ELECTRE III gives the possibility to introduce a *veto power* to certain criteria by associating with each one of these criteria a *veto threshold*, denoted v_j, such that $v_j \geqslant p_j$. The *discordance index* is used to take into account such a veto power. The veto power of each criterion is modeled through a *partial discordance index*, denoted $d_j(a, a')$, $j = 1, \ldots, n$, and defined as follows:

$$d_j(a,a') = \begin{cases} 1 & \text{if} \quad g_j(a) - g_j(a') < -v_j, \\ \frac{g_j(a) - g_j(a') + p_j}{p_j - v_j} & \text{if} \quad -v_j \leqslant g_j(a) - g_j(a') < -p_j, \\ 0 & \text{if} \quad g_j(a) - g_j(a') \geqslant -p_j. \end{cases} \tag{5}$$

Credibility index. The credibility index is defined as follows:

$$\sigma(a,a') = c(a,a') \prod_{j=1}^{n} T_j(a,a'), \tag{6}$$

where

$$T_j(a,a') = \begin{cases} \frac{1 - d_j(a,a')}{1 - c(a,a')} & \text{if } d_j(a,a') > c(a,a'), \\ 1 & \text{otherwise.} \end{cases} \tag{7}$$

This index reflects the way the assertion "a outranks a'" is more or less well justified or founded when taking into account all the criteria from F.

A.3.2. Interactions between criteria

This subsection provides the definitions of the three interaction types as they were defined in Figueira et al. (2009).

(a) *Mutual-strengthening effect between criteria g_j and g_i:*

Definition 4. *(Mutual-strengthening effect.) If criteria g_j and g_i both strongly, or even weakly, support the assertion aSa' (more precisely, $g_j, g_i \in \overline{C}(a'Pa)$), we consider that their contribution to the concordance index must be larger than the sum of $w_j + w_i$, because these two weights represent the contribution of each of the two criteria to the concordance index when the other criterion does not support aSa'.*

We suppose that the effect of the combined presence of $g_j, g_i \in \overline{C}(a'Pa)$ among the criteria supporting the assertion aSa' can be modeled by a mutual-strengthening coefficient, $k_{ji} > 0$, which intervenes algebraically in $c(a, a')$.

(b) *Mutual-weakening effect between criteria g_j and g_i:*

Definition 5. *(Mutual-weakening effect.) If criteria g_j and g_i both strongly, or even weakly, support the assertion aSa' (more precisely, $g_j, g_i \in \overline{C}(a'Pa)$), we consider that their contribution to the concordance index must be smaller than the sum of $w_j + w_i$, because these two weights represent the contribution of each of the two criteria to the concordance index when the other criterion does not support aSa'.*

We suppose that the effect of the combined presence of $g_j, g_i \in \overline{C}(a'Pa)$ among the criteria supporting the assertion aSa' can be modeled using a mutual-weakening coefficient, $k_{ji} < 0$, which intervenes algebraically in $c(a, a')$, such that $w_j + k_{ji} > 0$ and $w_i + k_{ji} > 0$.

(c) *Antagonism of criterion g_h over criterion g_j:*

Definition 6. *(Antagonistic effect.) If criterion g_j strongly, or weakly, supports the assertion aSa' and criterion g_h strongly opposes this assertion, we consider that the contribution of the criterion g_j to the concordance index must be smaller than the weight w_j that was considered in cases in which g_h does not belong to $\overline{C}(a'Pa)$.*

We suppose that this effect can be modeled by introducing an antagonism coefficient $k'_{jh} > 0$, which intervenes negatively in $c(a, a')$, such that $w_j - k'_{jh} > 0$.

Remark 1. *Let us notice that,*

- *Cases a and b are mutually exclusive, but cases a and c and cases b and c are not.*
- *For cases a and b, $k_{ji} = k_{ij}$.*
- *The presence of an antagonism coefficient $k'_{jh} > 0$ is compatible with both the absence of antagonism in the reverse direction ($k'_{hj} = 0$) and the presence of a reverse antagonism ($k'_{hj} > 0$).*

An additional coherency condition is needed.

Condition 1 (Positive net balance)**.**

$$w_j - \left(\sum_{\{j,i\}:\, k_{ji}<0} |k_{ji}| + \sum_h k'_{jh} \right) > 0, \quad \textit{for all} \quad g_j \in F.$$

This condition is necessary to avoid reducing the weights to zero or negative values.

A.3.3. An extension of the concordance index

The extension we consider in this paper is the one propose by Figueira et al. (2009). It takes into account the three interactions effects of the previous sections. Some additional notation is needed. Let

- $L(a, a')$ denote the set of all pairs $\{j, i\}$ such that $j, i \in \overline{C}(a'Pa)$;
- $O(a, a')$ denote the set of all ordered pairs (j, h) such that $j \in \overline{C}(a'Pa)$ and $h \in C(a'Pa)$.

The new formula of the concordance index is as follows.

$$\begin{aligned} c(a,a') &= \frac{1}{K(a,a')} \Bigg(\sum_{j\in\overline{C}(a'Pa)} c_j(a,a')w_j + \sum_{\{j,i\}\in L(a,a')} \mathcal{Z}\big(c_j(a,a'), c_i(a,a')\big)k_{ji} - \\ & \qquad - \sum_{(j,h)\in O(a,a')} \mathcal{Z}\big(c_j(a,a'), c_h(a',a)\big)k'_{jh} \Bigg) \end{aligned} \tag{8}$$

where

$$K(a,a') = \sum_{j\in F} w_j + \sum_{\{j,i\}\in L(a,a')} \mathcal{Z}\big(c_j(a,a'), c_i(a,a')\big)k_{ji} - \sum_{(j,h)\in O(a,a')} \mathcal{Z}\big(c_j(a,a'), c_h(a',a)\big)k'_{jh} \tag{9}$$

(It should be remarked that in the third summation $c_h(a', a)$ is always equal to 1.)

Remark 2. *For the current application we defined the $\mathcal{Z}-$function as follows: $\mathcal{Z}(x, y) = xy$. An explanation about this choice of this function can be found in Figueira et al. (2009).*

A.4. Exploiting the outranking relation

The exploitation procedure starts by deriving from the credibility degrees two complete pre-orders, $\mathcal{P}_\delta$ and $\mathcal{P}_\alpha$. A final partial pre-order $\mathcal{P}$ is built as the intersection of the two complete pre-orders. Pre-orders $\mathcal{P}_\delta$ and $\mathcal{P}_\alpha$ are obtained according to two variants of the same principle, both acting in an antagonistic way on the floating actions (Figueira et al., 2005b).

Definition 7 (Descending pre-order)**.** *The complete pre-order $\mathcal{P}_\delta$ is defined as a partition of the set A into r ordered classes, $\bar{B}_1$, ..., $\bar{B}_\ell$, ..., $\bar{B}_r$, where $\bar{B}_1$ is the head-class in $\mathcal{P}_\delta$. Each class $\bar{B}_\ell$ is composed of tied actions according to $\mathcal{P}_\delta$. The actions in class $\bar{B}_\ell$ are preferred to those in class $\bar{B}_{\ell+1}$. For this reason, $\mathcal{P}_\delta$ called a* descending *or* to-down *complete pre-order.*

Definition 8 (Ascending pre-order)**.** *The complete pre-order $\mathcal{P}_\alpha$ is defined as a partition of the set A into s ordered classes, $B_1, \ldots, B_\ell, \ldots, B_s$, where B_s is the head-class in $\mathcal{P}_\alpha$. Each class B_ℓ is composed of tied actions according to $\mathcal{P}_\alpha$. The actions in class $B_{\ell+1}$ are preferred to those in class B_ℓ. For this reason, $\mathcal{P}_\alpha$ called a* ascending *or* bottom-up *complete pre-order.*

The overall algorithm, composed by the procedures (called distillations) for determining $\mathcal{P}_\delta$, $\mathcal{P}_\alpha$, and then $\mathcal{P}$ can be succinctly outlined as follows.

1. Determine $\mathcal{P}_\delta$, starting the first distillation by defining an initial set $D_0 := A$. It leads to the first distilled $\bar{B}_1$. After getting $\bar{B}_\ell$, at the distillation $\ell + 1$, set $D_0 := A \setminus \{\bar{B}_1 \cup \cdots \cup \bar{B}_r\}$. Continue until all the actions in A are processed.
2. Determine $\mathcal{P}_\alpha$ by using a similar algorithm. But, now remember that the actions in $B_{\ell+1}$ are preferred to those in class B_ℓ.
3. The partial pre-order $\mathcal{P}$ will be computed as the intersection of $\mathcal{P}_\delta$ and $\mathcal{P}_\alpha$.

In the intersection of Step 3 there is incomparability when $\mathcal{P}_\delta$ and $\mathcal{P}_\alpha$ provide contradictory results and there is comparability when the results provided by these two pre-orders are compatible.

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