Assessing Different Possibilities for the Reuse of an Open-pit Quarry Using the Choquet Integral

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1. INTRODUCTION

It is well known that sustainable development is a multidimensional concept that considers different issues, such as socio-economic aspects, ecological factors, technical elements and ethical perspectives (World Commission, 1987). Measuring sustainability is often addressed through indicators able to represent the multidimensionality of the decision problem; these indicators must reflect the heterogeneous values that coexist in a decision-context and for this reason they are normally organized in specific sets and expressed by different measurement units (Boggia and Cortina, 2010).

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Therefore, sustainability assessment requires a multicriteria-based approach. Generally speaking, the techniques belonging to the family of multicriteria decision aiding (MCDA) are used to make a comparative assessment of alternative projects or heterogeneous measures (Roy and Bouyssou, 1995; Figueira *et al*., 2005a, 2005b). These methods allow several criteria to be taken into account simultaneously in a complex situation, and they are designed to help decision makers (DMs) to integrate the different options, which reflect the opinions of the involved actors, in a prospective or retrospective framework. Participation of the DMs in the process is a central part of the approach.

Sustainability is often considered in terms of the three pillars of environmental, social and economic considerations, and it has been generally agreed that policies, plans, programmes and projects should be prepared taking into account sustainability considerations. On the side of the evaluation procedures, which aim at assessing the overall sustainability of a territorial transformation project, mention can be made to the processes of environmental impact assessment (EIA) and strategic environmental assessment (SEA), which are defined at the European level by the Directives 1997/11/EC and 2001/42/EC, respectively. Both environmental impact assessment and strategic environmental assessment over time have increasingly considered not only the environmental effects of plans and projects, but also social and economic effects. Recently some applications started to think about sustainability as an integrated concept (Morrison-Saunders and Therivel, 2006). There is no single definition of integrated sustainability assessment, and several approaches are nowadays available with different levels of integration (Figure 1).

When dealing with sustainability assessment in an integrated way, a critical issue is how to combine the different dimensions in the evaluation framework. Following the approach that has been proposed by Jesinghaus (1999), the performance of a certain strategy (plan, programme, project, policy, etc.) in terms of sustainability can be computed by combining different criteria (or indicators) through a specific procedure that allows the original values to be aggregated in a composite index, which reflects the overall sustainability of the topic under examination.

In this context, of particular importance is the degree of compensability between the different dimensions/aspects of the problem. In this sense, when dealing with sustainability issues, it has been noticed that neither an economic reductionism nor an ecological one is possible (Munda, 2005). Because in general, economic sustainability has an ecological cost, and ecological sustainability has an economic cost, an integrative evaluation framework is needed for tackling sustainability issues properly.

From a computational point of view, the task of dealing with sustainability assessment following an integrated approach cannot be addressed through the linear combination. This operation, in fact, does not fit with the problem because the overall effect is not only the sum of the different effects; in other words, the principle of substitution cannot be applied in this context, where a good performance in one area (for example, the economic dimension) is not compensated by a poor performance in another area (for example, the environmental dimension) (Giove *et al*., 2011).

As a consequence, it is necessary to overcome the conceptual and practical limitations associated with this kind of approach and tackle the problem with a nonlinear aggregation method that takes into account the potential interactions between variables, considering also the synergy and redundancy effects among criteria.

Thus, the present contribution addresses the problem of the integration in sustainability assessment by means of the Choquet integral (Choquet, 1953; Sugeno, 1974), which provides a computational structure for aggregating

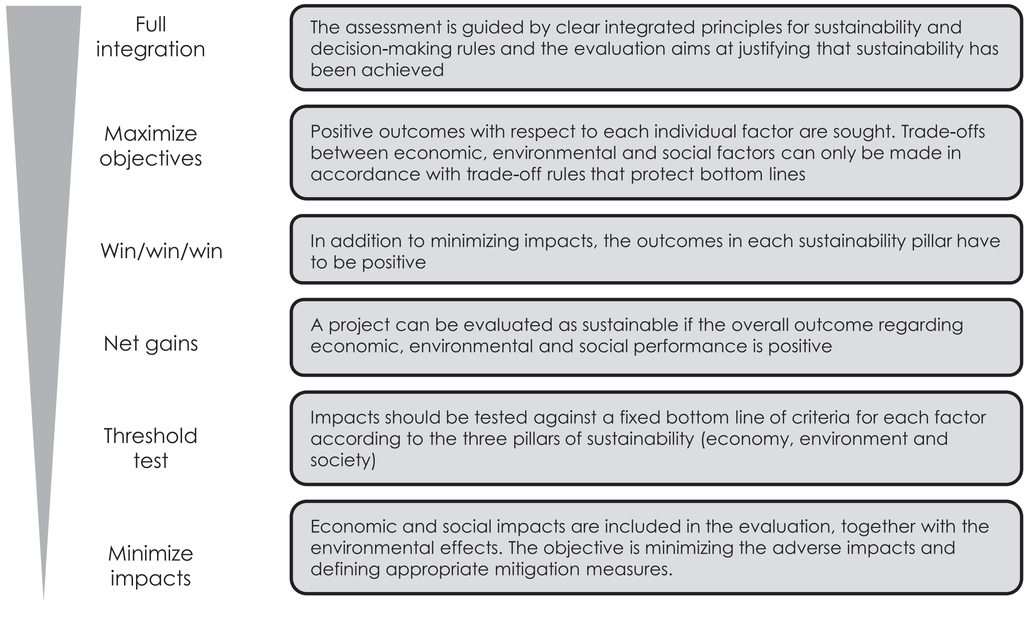

Figure 1. Existing approaches for addressing the issue of integrated sustainability assessment (source: adapted from Morrison-Saunders and Therivel, 2006).

information, taking into account interactivity between criteria. Starting from a real application concerning the evaluation of alternative options for the requalification of an abandoned quarry in the Province of Novara (Northern Italy), the paper aims at exploring the contribution that the Choquet integral offers in sustainability assessment of urban and territorial transformation projects.

In fact, the usefulness and the potential of this tool is particularly real for the analysis of concepts such as the sustainability one, for which the substitution principle can be not suitable and where it is necessary to consider and assess the levels of synergy between the sustainability dimensions (environment, society and economy).

In this context, it is worth recalling that there are two competing theories about sustainability, one referring to the weak sustainability approach and the other to the strong sustainability approach (Pearce and Atkinson, 1993; Pearce *et al*., 1996). The central element that distinguish the two theories is the assumption that human-made capital can effectively substitute for natural capital and the services provided by the ecological system. This is the perspective supported by the weak sustainability theory. On the other hand, the strong sustainability approach calls for maintaining human, human-made and natural capital separately (Costanza and Daly, 1992).

After the introduction, the rest of the paper is organized as follows: Section 2 provides the background methodology concerning non-additive measures (NAM) and Choquet integral; Section 3 illustrates the performed application, considering the description of the case study, the structuring of the decision problem and the development of the model; Section 4 discusses the main findings of the work; and Section 5 summarizes the conclusions that can be drawn from the research done.

2. NON-ADDITIVE MEASURES AND CHOQUET INTEGRAL

2.1. Methodological background

Criteria are used for evaluating decision-making problems. It has been noticed that in many decision problems criteria consist of interdependent and interaction characteristics and they cannot be evaluated and aggregated by conventional additive measures, such as the weighted average method.

In order to address this topic, many methods have been proposed in the multi-attribute value theory context and they belong to the family of the NAM. It is widely recognized that the NAM approach satisfies many theoretical requirements, and it is able to model many types of interactions in the preference structure of the DM.

The Choquet integral belongs to the NAM family, and it represents a flexible aggregation operator being introduced by Choquet (1953) as the generalization of the weighted average method to interactions among criteria.

The Choquet integral method can be seen as a fuzzy integral method based on any fuzzy measure that provides an alternative computational structure for aggregating information (Grabisch, 1996).

The basic idea is to assign a weight to every possible set of criteria and to compute a weighted average of the values of all the subsets. This operation allows coalitions of criteria to be taken into account, instead of single criteria only, as in the weighted average method.

Note that the numerical complexity increases exponentially with the number of parameters involved. If n is the number of criteria, the Choquet integral requires the specification of 2^n parameters (which represent all the possible combinations of the n criteria).

Let 2^N be the power set of N (i.e. the set of all the subsets of the set of criteria N); a fuzzy measure (or capacity) on N is defined as a set function $\mu : 2^N \rightarrow [0,1]$, which satisfies the following properties:

a) $\mu(0) = 0; \mu(N) = 1$ (boundary conditions);
b) $\forall S \subseteq T \subseteq N, \mu(S) \leq \mu(T)$ (monotonicity condition).

In the framework of multicriteria decision problems, the value $\mu(S)$ given by the fuzzy measure μ on the set of criteria S is related to the importance weight given by the DM to the set of criteria S (Angilella *et al*., 2010; Angilella *et al*., 2004; Grabisch, 1996).

A fuzzy measure is said to be additive if $\mu(S \cup T) = \mu(S) + \mu(T)$ for any $S, T \subseteq N$ such that $S \cap T = \phi$.

Otherwise, the fuzzy measure is non-additive, and it can be superadditive if $\mu(S \cup T) \geq \mu(S) + \mu(T)$ or subadditive if $\mu(S \cup T) \leq \mu(S) + \mu(T)$. For an additive measure, no interaction is possible among the criteria and the linear superposition holds. For a subadditive measure, a redundant effect is modelled, whereas the contrary holds for a superadditive effect, called synergic effect.

Given a non-additive measure μ, let us consider $(x_1, x_2, \ldots, x_n)$, the criteria values of a particular alternative. The Choquet integral of the vector $(x_1, x_2, \ldots, x_n)$ with reference to a capacity μ is given by the following equation:

$$Ch([x_1, x_2, \ldots, x_n], \mu) = \sum_{i=1}^{n} \left(x_{(i)} - x_{(i-1)}\right)^* \mu\left(A_{(i)}\right) \quad (1)$$

being (.) an index permutation so that $x_{(i)} \le x_{(i+1)}$, $i = 1, 2, \ldots n$-1, $x_{(0)} = 0$.

Figure 2 provides a geometrical representation of the Choquet integral.

Several applications of the Choquet integral in MCDA exist in the literature, where it is possible to find a wide range of experimentations (Grabisch and Labreuche, 2008). This framework has been applied for addressing logistic processes (Demirel *et al.*, 2010; Berrah and Cliville, 2007; Tsai and Lu, 2006), economic evaluation (Heilpern, 2002), social analysis (Meyer and Ponthiere, 2011), whereas applications in sustainability assessment and environmental analysis are less consolidated (FEEM, 2009; Giove *et al.*, 2011).

Mention should also be made to the adaptation of the Choquet integral in other MCDA techniques, such as analytic hierarchy process (AHP) (Lin, 2008; Hu and Chen, 2010; Lee *et al.*, 2011) and analytic network process (Lang *et al.*, 2009; Yazgan *et al.*, 2010) in order to consider the existence of interactions among criteria.

2.2. The capacity identification problem

It is necessary to put in evidence that a fundamental issue in the practical application of the Choquet integral is to determine a capacity, if it exists, so that the Choquet integral can represent the revealed preference of the DM.

As we saw in Section 2.1, as a capacity is defined on the power set of *N*, the complexity of the problem increases exponentially, becoming inacceptable for large sets of criteria.

In order to cope with this difficulty, many simpler models have been proposed in the literature, where the capacity is restricted to some particular subspaces (Grabisch *et al.*, 2008). Among the available approaches, a key role is played by the so-called *k*-additive capacities (Grabisch, 1997) because the value of *k* is related to the complexity of the model (i.e. the number of subsets of at most *k* elements). Particularly, the 2-additive model seems to be of specific interest as it has a clear interpretation in many decision problems. Several applications exists if the Choquet integral with reference to a 2-additive capacity in different domains (Grabisch *et al.*, 2002; Berrah and Clivillè, 2007). where it is put in evidence that the approach offers a good compromise between flexibility of the model and complexity.

We describe the case of the Choquet integral with reference to a 2-additive capacity as follows.

To start with, it is necessary to define the Mobius transformation (Grabisch *et al.*, 2003) of the capacity μ as represented in Equation (2):

$$a_T = \sum_{S \subseteq T} (-1)^{t-s} \mu(S) \quad \forall T \subseteq N, s = |S|, t = |T| \qquad (2)$$

We can observe that if $T = \{i\}$ is a singleton, then $\mu(\{i\}) = a(\{i\})$. If $T = \{i,j\}$ is a couple of criteria, then $\mu(\{i,j\}) = a(\{i\}) + a(\{j\}) + a(\{i,j\})$.

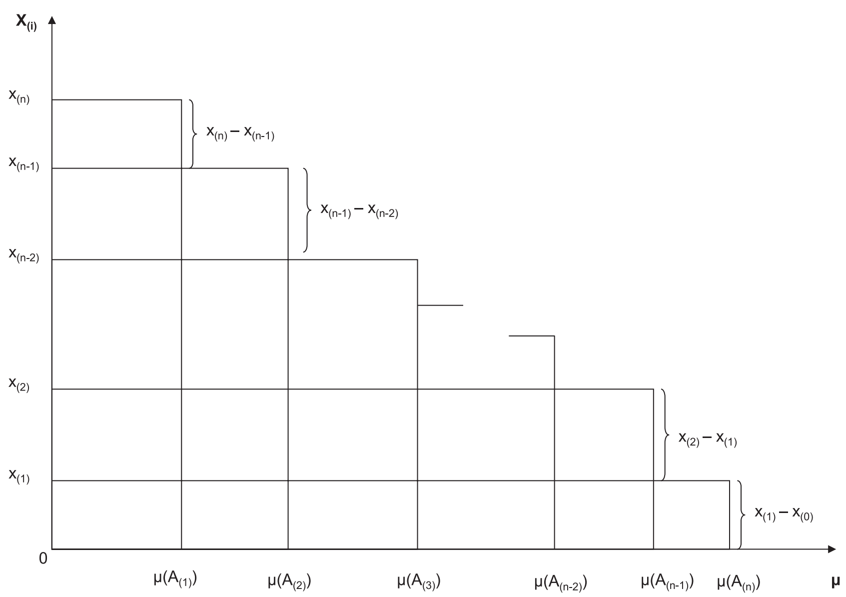

Figure 2. Geometrical representation of the Choquet integral

A capacity μ on N is said to be 2-additive if (Mayag *et al*., 2011):

- for all subset T of N such that $|T| \succ 2, a_T = 0$;
- there exists a subset B of N such as $|B| = 2, a_B \neq 0$.

Some indices have been introduced in game theory (Shapley, 1953) that can be used in the context of MCDA in order to measure the importance and the interaction among criteria. The most important indices are the Shapley value and the interaction index.

The importance index (or Shapley value) of criterion $i \in N$ with respect to the capacity μ is given in Equation (3):

$$\varphi(\{i\}) = \sum_{\mathrm{T} \subseteq \mathrm{N}\ \{i\}} \frac{\mathrm{a}(\mathrm{T} \cup \{\mathrm{i}\})}{|\mathrm{T}| + 1} \tag{3}$$

The interaction index between criteria $i, j \in N$ with respect to the capacity μ is given in Equation (4) (Murofushi and Soneda, 1993):

$$\varphi(\{\mathrm{i},\mathrm{j}\}) = \sum_{\mathrm{T} \subseteq \mathrm{N}\ \{\mathrm{i},\mathrm{j}\}} \frac{\mathrm{a}(\mathrm{T} \cup \{\mathrm{i},\mathrm{j}\})}{|\mathrm{T}| + 1} \tag{4}$$

It has been showed that the Choquet integral with reference to a 2-additive capacity is entirely described by the Shapley index and the interaction index for pairs of criteria, needing only $\frac{n(n+1)}{2} - 1$ values to be defined. More formally, it can be represented by Equation (4) (Mayag *et al*., 2011):

$$Ch([x_1, x_2, \ldots, x_n], \mu) = \sum_{i=1}^{n} \varphi(\{i\}) x_i - \frac{1}{2} \sum_{\{i,j\} \subseteq N} \varphi(\{i,j\}) \left| x_i - x_j \right| \tag{5}$$

3. APPLICATION TO THE CASE STUDY

3.1. Research objectives and description of the case study context

The decision problem under analysis concerns the evaluation of alternative options for the requalification of an abandoned quarry located in the Province of Novara (Northern Italy). In particular, the study concerns the analysis and the comparison of five alternatives in order to select the most sustainable one.

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).

The area under analysis (Figure 3) 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. Because of 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.

The purpose of the present analysis is to experiment the application of the Choquet integral approach for the comparison of the alternative options for the requalification of the abandoned quarry and for the synthesis of the available data concerning the decision problem under examination, in order to highlight the most sustainable solution.

In particular, the specific objective of the application is to explore limits and potentialities of the Choquet integral approach in the context of sustainability assessments of territorial transformation projects, where several trade-offs exist among the conflicting aspects involved in the decision.

The involvement of several experts with different backgrounds and interests allowed us to implement a

Figure 3. The abandoned open-pit quarry.

multidisciplinary/interdisciplinary approach. In terms of interdisciplinarity, the issue is to find agreement on the set of criteria to be used; in terms of multidisciplinarity, the issue is to propose and compute an appropriate criterion score. The efficiency of the interaction process can greatly increase its effectiveness, too (Munda, 2005).

3.2. Presentation of the alternatives

For the reclamation of the area five alternative projects were considered by the municipal authority that can be described as follows: (i) basic reclamation; (ii) realization of a forest; (iii) development of a wetland; (iv) implementation of the ecological network; and (v) construction of a recreational structure.

Table I shows the description of the five alternative options that were proposed for the requalification of the abandoned quarry.

In order to better clarify the description of the alternative projects, Figure 4 shows a visual example of the five scenarios under evaluation.

3.3. Problem structuring and model development

The problem definition overlaps the decision-making intelligence phase, which refers to the structuring of the problem, the identification of the objectives, and the selection of criteria or attributes to describe the degree of achievement of each objective (Simon, 1960).

The comparison of different projects for the reuse of an abandoned quarry represents a complex planning problem in which the presence of interrelated elements and conflicting aspects suggests the use of a multicriteria decision analysis that is able to provide a rational base for the systematic analysis of the alternative options. Because of the aforementioned complexity of the problem under analysis, and with the aim of explicitly considering the interrelationships and the trade-offs between the aspects involved in the decision, an approach based on NAM and the Choquet integral has been applied.

Starting from the overall objective of the analysis, which is the identification of the most sustainable option for the reuse of the abandoned quarry, a comprehensive set of evaluation criteria that reflect all the concerns relevant to the decision problem has been identified. Taking into account the full range of aspects relevant to the decision problem enhances the quality of the final decision, allowing the totality of the effects of the transformation project to be considered, and the negative externalities and the intergenerational effects to be minimized (Bottero and Ferretti, 2011).

Particularly, in the present study, 18 indicators have been identified, clustered in four main criteria including economic, social, environmental and legislative/institutional aspects (Figure 5).

More specifically, the ‘economic aspects’ criterion aims at considering the economic and financial element of the problem, taking into account both the cost and the financial efficiency of the investment and the consequences that the operation could determine on the economic system in terms of local income. The ‘social aspects’ criterion concerns the new services created for the population, considering

Table I. The alternative scenarios for the reuse of the abandoned quarry

Alternative		Description
A1	Simple reclamation	This scenario involves the filling of the quarry using proper material coming from building demolition activities, the arrangements of security measures for the banks, the laying of topsoil, the natural evolution of the vegetation on the covered area and the accelerating growth of the autochthonous locust tree wood.
A2	Forest	This project provides the filling of the quarry using proper material coming from building demolition activities, the arrangements of security measures for the banks, the laying of topsoil, the cover with drainage material and the establishment of an oak-hornbeam wood.
A3	Wetland	This recovery hypothesis involves the partial filling of the quarry, the arrangements of security measures for the banks, the surface sealing, the partial realization of a lake, the planting of wetland vegetation and the natural evolution of the surrounding wood and the wetland.
A4	Ecological network	This scenario regards the partial filling of the quarry, arrangements of security measures for the banks, the surface sealing, the realization of lakes, the construction of pedestrian and equestrian pathways and of recreational areas, the predisposition of information and educational material and in the development of the existing wood.
A5	Recreational structure	This alternative project provides the partial filling of the quarry, the arrangements of security measures for the banks in order to allow the construction a recreational and sportive structure (or residential structure) on the base of the ClimateHouse model, completely self-sufficient in terms of energy and wastewater disposal and in harmony with the landscape matrix.

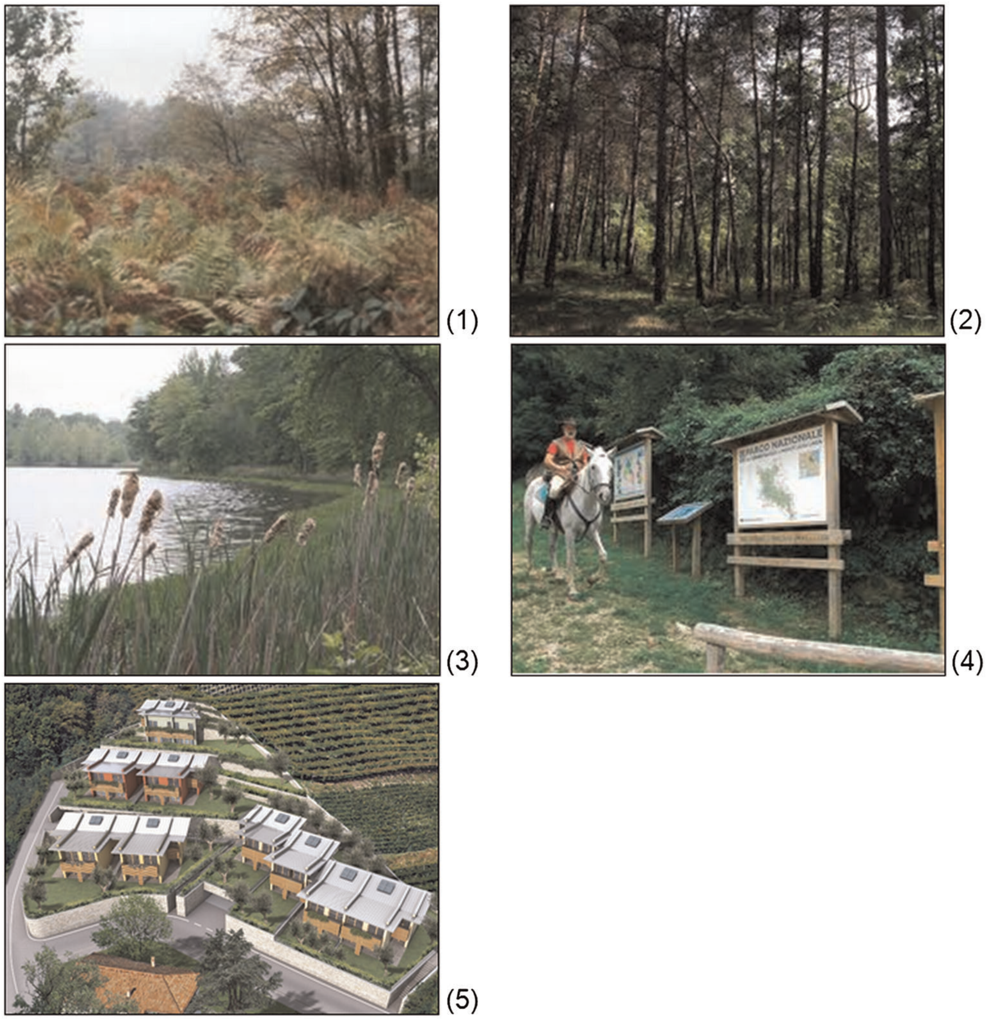

Figure 4. Alternative reuse scenarios: (1) basic reclamation; (2) forest; (3) wetland; (4) ecological network; and (5) recreational structure.

also the phenomenon of social opposition that could affect this kind of territorial transformation. The ‘environmental aspects’ are related to the effects that the project is likely to produce on the environmental system, considering both the biotic components and the a-biotic factors. Finally, the ‘institutional aspects’ criterion regards the constrains that could affect the transformation project.

Furthermore, in order to provide a complete explanation, Table II shows in detail the description of each indicator identified in the model. The arrow indicates if the described indicator assesses an effect or an action to be maximized ($\uparrow$) or to be minimized ($\downarrow$) with reference to the alternative’s performance to be evaluated.

The criteria considered in the present application were selected based on the relevant international literature (Bascetin, 2007; Soithanmohammadi *et al*., 2010; Golestanifor and Aghasani Bazzari, 2010) and on the requirements coming from the legislative framework in the context of EIA (first of all, the European Directive 11/97).

3.4. Evaluation of the alternatives

According to their performance, the five alternatives were evaluated with reference to each attribute. The judgments were assigned using a 0–1 points scale where the value 0 indicates a very low performance and the value 1 indicates a very high performance in

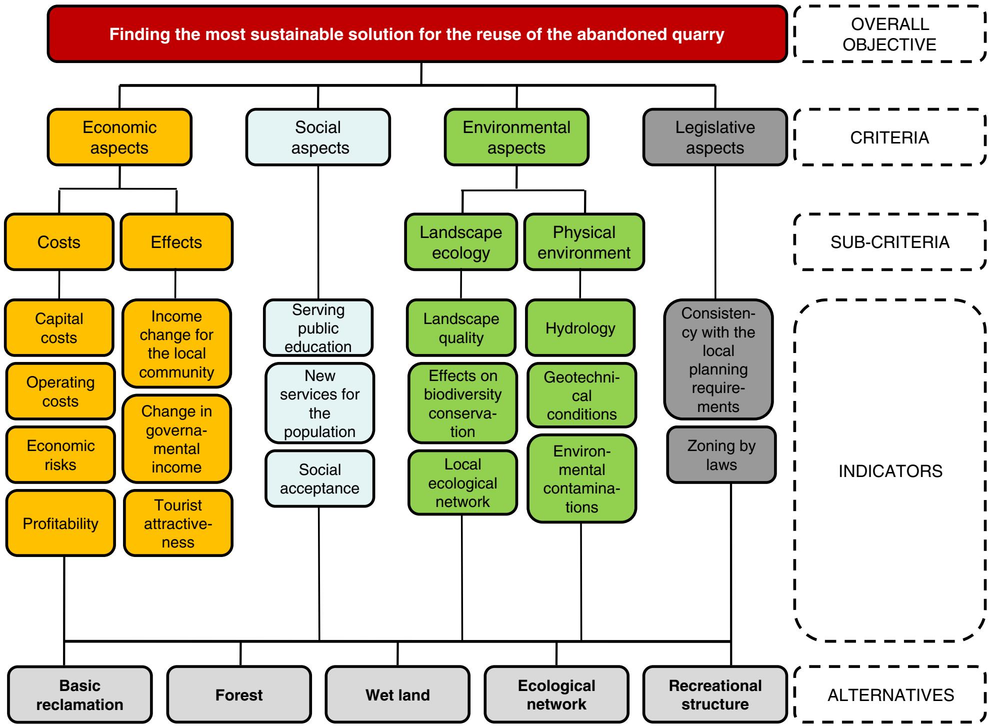

Figure 5. The decision model for the analysis.

terms of sustainability. Moreover, intermediate values between the minimum and the maximum have been identified, and in detail, the value 0.25 indicates a low performance, the value 0.5 indicates a medium performance and finally the value 0,75 for a high performance. Mention should also be made to the fact that the problem under analysis involves both criteria that positively affects the decision (whose corresponding attributes have thus to be maximized) and criteria that negatively affects the decision (whose corresponding attributes have thus to be minimized).

Table III shows the result of the alternative evaluation phase.

3.5. Aggregation of indicators and weighting of criteria

With reference to the decision tree previously described, the elements have been aggregated at different levels. The result coming at the final node of the tree provides the overall sustainability value of the alternatives.

At each level of the decision tree, the procedure that has been followed in this application (Despic and Simonovic, 2000; Giove *et al*., 2011) requires to attribute a weight to the coalition of attributes that belong to the same node. A matrix is then created, for each node of the decision tree, where all the possible combinations of attributes are embodied. The matrix is presented to a respondent, who is asked to express his/her preferences about the various scenarios. Particularly, the different combinations of attributes are evaluated in a 0–10 points scale where the value 0 means that the combination is not desirable at all, whereas the value 10 indicate a very attractive combination.

The questionnaire had a page for each of the nodes of the hierarchical tree; each page contained a matrix representing all the possible combinations among the attributes belonging to a specific node.

As an example, Table IV represents the evaluation table that was submitted in the questionnaire in the case of the sustainability node. The first three columns report the performance of the four criteria (good or bad) whereas the fourth column contains the evaluation of the DM. In order to better clarify the questioning process, the question concerning the seventh row of the table was of the type: ‘How would you score an hypothetical case where economic aspects and social aspects are good while environmental aspects and institutional aspects are bad?’

Mention has to be made to the fact that for the lower levels of the hierarchy, the evaluation has been performed by individual experts in their proper field

Table II. Indicators' description

Indicators			Description	
Economic aspects	EC1	Capital costs	Direct and investment costs for project construction and realization	↓
	EC2	Operating costs	Costs related to the management and maintenance of the project	↓
	EC3	Economic risks	The criterion refers to the assessment of the economic and financial feasibility in uncertainty conditions	↓
	EC4	Profitability	The criterion refers to the financial efficacy of the investment and to the consequences that the project may determine on the local economical system in terms of public revenues.	↑
	EC5	Income change for the local community	The criterion considers the changes in economic benefits for the local community as a consequence of the offer of employment opportunities.	↑
	EC6	Change in governmental income	The criterion considers the changes in economic benefits for the local administration through the increase in investment opportunities.	↑
	EC7	Tourist attractiveness	The criterion considers the economic benefits derived from an increase of the tourist attractiveness of the area.	↑
Social aspects	SO1	Serving public education	The criterion refers to the creation of opportunities of environmental education in order to improve the understanding of the sustainable development concept.	↑
	SO2	New services for the population	The criterion refers to the integration of the resources and the infrastructures for the population.	↑
	SO3	Social acceptance	The criterion considers the positive feedback from the population in terms of appreciation of the project consequences.	↑
Environmental aspects	EN1	Landscape quality	The criterion refers to the restoration of the landscape in the abandoned area by preserving its environmental and ecological value.	↑
	EN2	Effects on biodiversity conservation	The criterion refers to the implementation of actions of recovery and preservation with the aim of improving plant and animal biodiversity.	↑
	EN3	Local ecological network	The criterion refers to the environmental requalification of the area in order to preserve, expand and valorize the existing ecological network.	↑
	EN4	Hydrology	The criterion concerns the assessments of the impacts generated by the requalification project and of the interferences on the hydrological quality of the area.	↓
	EN5	Geotechnical conditions	The criterion refers to geotechnical considerations concerning the slope stability of the reservoir.	↑
	EN6	Environmental contaminations	The criterion concerns the impacts on the physical environment deriving from the project realization.	↓
Institutional aspects	IN1	Consistency with the local planning requirements	The criterion refers to the project's consistency with the indications of the different land use plans (municipal, provincial and regional) for the abandoned quarry management.	↑
	IN2	Zoning by laws	The criterion takes into consideration the constraints relating to the zoning of the land according to the local planning instruments.	↑

Table III. Evaluation of alternatives

Indicators		Alternatives				
		A1	A2	A3	A4	A5
EC1	Capital costs	1	1	0.75	0.75	0
EC2	Operating costs	1	0.75	1	0.75	0
EC3	Economic risk	1	1	1	1	0.25
EC4	Profitability	0.25	0.25	0	0	1
EC5	Change in income of local community	0	0	0	0.5	1
EC6	Change in governmental income	0	0	0	0	0.75
EC7	Tourism attraction	0	0	0.25	1	1
SO1	Serving public education	0	0.25	0.75	1	0.25
SO2	New services for population	0	0.75	0.75	1	1
SO3	Social acceptance	0	0.75	0	1	0.75
EN1	Landscape quality	0.25	1	1	1	0.75
EN2	Effects on biodiversity conservation	0.75	1	1	0.5	0
EN3	Local ecological network	0	0.5	0.5	1	0
EN4	Effects on hydrology	0.25	0.25	1	1	0.5
EN5	Geotechnical conditions	0.5	1	1	1	0.25
EN6	Environmental contaminations	1	1	1	0.75	0
IN1	Consistency with local planning requirements	0.5	0.5	0.75	1	0
IN2	Zoning by laws	1	1	1	1	0

Table IV. Example of valuation table

Economic aspects	Environmental aspects	Institutional aspects	Social aspects	Evaluation
Bad	Bad	Bad	Bad	0
Good	Bad	Bad	Bad	
Bad	Good	Bad	Bad	
Bad	Bad	Good	Bad	
Bad	Bad	Bad	Good	
Good	Good	Bad	Bad	
Good	Bad	Good	Bad	
Good	Bad	Bad	Good	
Bad	Good	Good	Bad	
Bad	Good	Bad	Good	
Bad	Bad	Good	Good	
Good	Good	Good	Bad	
Good	Bad	Good	Good	
Bad	Good	Good	Good	
Good	Good	Bad	Good	
Good	Good	Good	Good	10

of expertise. In this case, different experts in the context of environmental engineering and sustainability assessment have been involved in the compilation of the matrixes.

As an example, Table V represents the questionnaire that has been submitted in order to evaluate the combinations of the elements belonging to the ‘social aspects’ criterion. Let us consider the last-to-one row of the matrix in Table III. In this case, the question was of the type: ‘How do you evaluate an hypothetical scenario where serving public education and new services for the population are good, while social acceptance is bad?’ In this case, a synergy has been recognized by the respondent among the attributes and this leads to have a score of 9 for the combination of the elements ‘serving public education’ and ‘new

Table V. Scores attributed to the 'social aspects' criterion

Social acceptance	Serving public education	New services for population	Evaluation
Bad	Bad	Bad	0
Good	Bad	Bad	2
Bad	Good	Bad	3
Bad	Bad	Good	4
Good	Good	Bad	5
Good	Bad	Good	7
Bad	Good	Good	9
Good	Good	Good	10

services for the population' that is higher than the sum of the single elements (third and fourth rows of the matrix the Table V). Following this example, Figure 6 shows in a geometrical way the calculation of the Choquet integral for alternative 5. The initial scores of alternative 5 (0.75, 0.25 and 1 for social acceptance, serving public education and new services for population, respectively) have been aggregated according to formula (1) by using the weights established in Table V; the result of the calculations is 7. Mention has to be made to the fact that in the aggregation procedure followed in the application, the weights of attributes and criteria are given in a 0–10 points scale. According to this procedure, where no aggregation among the parameters of the model is required (i.e. there is only one attribute belonging to a node of the decision tree), the initial scores are multiplied for ten in order to obtain homogeneous values at each level of the decision tree.

For the higher level of the hierarchy (the criteria level), the aggregation of the elements followed a different procedure. Mention has to be made to the fact that at this level, the evaluation of the importance of the criteria refer to a political sphere, and it does not reflect a strict objective and technical knowledge (FEEM, 2009). These considerations led us to ask different stakeholders involved in the decision problem to express their preferences about the criteria of the model. Seven real actors (an agronomist who has his professional bureau in the area, a group of local inhabitants, the private entrepreneur who might be interested in the transformation project, an architect from the Province of Novara, a delegate from the Forestry Corp, an official from the Municipal Technical Office and the Major) have been questioned separately. Table VI represents the evaluation made by the seven actors, and the final average values that have been considered for the calculations.

Again, in this case, different synergies and redundancies among the criteria have been identified, and the measure of the importance of some coalition turned out to be superadditive or subaddictive. In order to stress the importance of considering criteria interactions in decision problems related to sustainability assessment, it is interesting to examine a couple of examples in Table VI showing the existence of synergies and redundancies among criteria. To start with, let us consider the coalition of environmental and economic

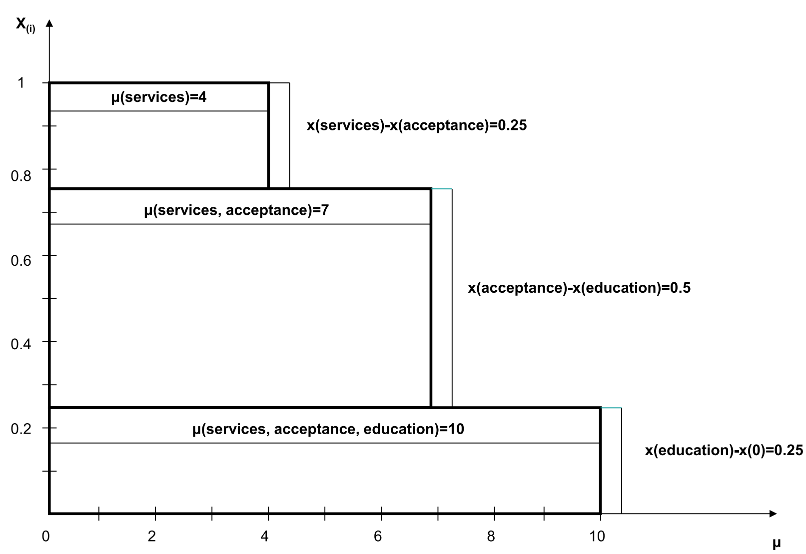

Figure 6. Geometrical representation of the Choquet integral for calculating the score of the alternative 5 with reference to social aspects.

Table VI. Scores attributed to the ‘sustainability’ node

Eco	Env	Inst	Soc	Agro	Pop	Ent	Arch	F cor	T off	Maj	Average
B	B	B	B	0	0	0	0	0	0	0	0.00
G	B	B	B	1	2	5	2	1	1	1	1.86
B	G	B	B	3	5	3	3	3	2	4	3.29
B	B	G	B	5	1	2	4	5	4	3	3.43
B	B	B	G	2	3	1	1	2	2	2	1.86
G	G	B	B	4	8	9	6	5	4	6	6.00
G	B	G	B	6	3	7	5	5	4	4	4.86
G	B	B	G	4	6	7	4	4	4	4	4.71
B	G	G	B	8	6	5	6	7	5	7	6.29
B	G	B	G	6	9	5	5	6	5	7	6.14
B	B	G	G	7	4	3	4	6	5	5	4.86
G	G	G	B	9	8	9	8	8	7	8	8.14
G	B	G	G	9	6	8	6	7	7	6	7.00
B	G	G	G	9	9	6	7	8	8	8	7.86
G	G	B	G	7	10	10	9	9	9	9	9.00
G	G	G	G	10	10	10	10	10	10	10	10.00

Eco, ecological aspects; Env, environmental aspects; Inst, institutional aspects; Soc, social aspects; Agro, agronomist; Pop, population; Ent, entrepreneur; Arch, architect; F cor, Forestry Corp; T off, Municipal Technical Office; Maj, Major.

aspects. In this case, the measure is 6, that is higher than the sum of the importance of the single criteria (1.86 and 3.29, respectively), and a synergy is recognized. In fact, a project characterized by a high performance of environmental aspect is often described by high costs of intervention, and therefore a project with high environmental quality and low costs is very well appreciated. So, it is possible to say that the comprehensive importance of the two criteria is higher than the sum of importance of the two criteria considered separately. On the side of the redundancy, let us examine the coalition of institutional and social aspects. In this case, the measure is 4.86, that is lower than the sum of the importance of the single criteria (3.43 and 1.86, respectively), and a redundancy is identified. In fact, a project that is consistent with institutional requirements very often provides also a lot of services for the population. In this case, thus, their comprehensive importance is lower than the sum of the importance of the two criteria.

Table VII. Overall results of the performed evaluation

<table>
<tr><th>CRITERIA</th><th>SUB-CRIT.</th><th>IND.</th><th colspan="4">ALTERNATIVE 1</th><th colspan="4">ALTERNATIVE 2</th><th colspan="4">ALTERNATIVE 3</th><th colspan="4">ALTERNATIVE 4</th><th colspan="4">ALTERNATIVE 5</th></tr>
<tr><td rowspan="7">ECON. ASPECTS</td><td rowspan="4">Costs</td><td>EC1</td><td>1</td><td rowspan="4">7.75</td><td rowspan="7">23.25</td><td rowspan="18">381.793</td><td>1</td><td rowspan="4">7.50</td><td rowspan="7">22.50</td><td rowspan="18">597.260</td><td>0.75</td><td rowspan="4">6.50</td><td rowspan="7">23.00</td><td rowspan="18">682.345</td><td>0.75</td><td rowspan="4">6.00</td><td rowspan="7">49.50</td><td rowspan="18">852.930</td><td>0</td><td rowspan="4">5.00</td><td rowspan="7">75.50</td><td rowspan="18">436.00</td></tr>
<tr><td>EC2</td><td>1</td><td>0,75</td><td>1</td><td>0.75</td><td>0</td></tr>
<tr><td>EC3</td><td>1</td><td>1</td><td>1</td><td>1</td><td>0.25</td></tr>
<tr><td>EC4</td><td>0.25</td><td>0,25</td><td>0</td><td>0</td><td>1</td></tr>
<tr><td rowspan="3">Econ. effects</td><td>EC5</td><td>0</td><td rowspan="3">0.00</td><td>0</td><td rowspan="3">0.00</td><td>0</td><td rowspan="3">0.50</td><td>0.5</td><td rowspan="3">4.50</td><td>1</td><td rowspan="3">9.25</td></tr>
<tr><td>EC6</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0.75</td></tr>
<tr><td>EC7</td><td>0</td><td>0</td><td>0.25</td><td>1</td><td>1</td></tr>
<tr><td rowspan="3">SOCIAL ASPECTS</td><td rowspan="3"></td><td>SO1</td><td>0</td><td rowspan="3">0.00</td><td rowspan="3">0.00</td><td>0,25</td><td rowspan="3">6.00</td><td rowspan="3">60.00</td><td>0.75</td><td rowspan="3">6.75</td><td rowspan="3">67.50</td><td>1</td><td rowspan="3">10.00</td><td rowspan="3">100.00</td><td>0.25</td><td rowspan="3">7.00</td><td rowspan="3">70.00</td></tr>
<tr><td>SO2</td><td>0</td><td>0,75</td><td>0.75</td><td>1</td><td>1</td></tr>
<tr><td>SO3</td><td>0</td><td>0</td><td>0</td><td>0.25</td><td>0.5</td></tr>
<tr><td rowspan="6">ENV. ASPECTS</td><td rowspan="3">Land./ Ecol.</td><td>EN1</td><td>0.25</td><td rowspan="3">2.75</td><td rowspan="6">40.50</td><td>1</td><td rowspan="3">7.50</td><td rowspan="6">79.00</td><td>1</td><td rowspan="3">7.50</td><td rowspan="6">85.00</td><td>1</td><td rowspan="3">8.00</td><td rowspan="6">87.00</td><td>0.75</td><td rowspan="3">1.50</td><td rowspan="6">22.00</td></tr>
<tr><td>EN2</td><td>0.75</td><td>1</td><td>1</td><td>0.5</td><td>0</td></tr>
<tr><td>EN3</td><td>0</td><td>0,5</td><td>0.5</td><td>1</td><td>0</td></tr>
<tr><td rowspan="3">Physical env.</td><td>EN4</td><td>0.25</td><td rowspan="3">6.00</td><td>0,25</td><td rowspan="3">8.50</td><td>1</td><td rowspan="3">10.00</td><td>1</td><td rowspan="3">9.75</td><td>0.5</td><td rowspan="3">3.25</td></tr>
<tr><td>EN5</td><td>0.5</td><td>1</td><td>1</td><td>1</td><td>0.25</td></tr>
<tr><td>EN6</td><td>1</td><td>1</td><td>1</td><td>0.75</td><td>0</td></tr>
<tr><td rowspan="2">INST. ASPECTS</td><td rowspan="2"></td><td>IN1</td><td>0.5</td><td rowspan="2">6.50</td><td rowspan="2">65.00</td><td>0,5</td><td rowspan="2">6.50</td><td rowspan="2">65.00</td><td>0.75</td><td rowspan="2">8.25</td><td rowspan="2">82.50</td><td>1</td><td rowspan="2">10.00</td><td rowspan="2">100.00</td><td>0</td><td rowspan="2">0.00</td><td rowspan="2">0.00</td></tr>
<tr><td>IN2</td><td>1</td><td>1</td><td>1</td><td>1</td><td>0</td></tr>
</table>

4. RESULTS AND DISCUSSION

4.1. Final priorities of the alternative options

The application of the measures of Table VI to the scores coming from previous aggregation provides the final priorities of the alternatives.

According to the calculations that have been made, the most sustainable alternative is the ecological network (852.93), followed by the humid area (682.345), then the forest area (597.26), the resort (436.17) and finally the simple recovery solution (381.793).

Moreover, taking into account the partial scores of the alternatives (Table VII), we can find further interesting results. To start with, alternative 4 is has highest priorities according to all the considered criteria; secondly, alternatives 2 and 3 have very low priorities from the economic point of view and higher priorities regarding to other criteria; finally, alternatives 1 and 5 have not balanced priorities among the four criteria.

4.2. Analysis of the available analytical approaches for the decision problem

There is a whole range of existing decision-aiding techniques that could be applied to support sustainability assessments, some extending upwards from EIA and others downwards from policy analysis.

As it is generally recognized, no MCDA technique is the 'best' for all problems, and the various methods often produce different results for the same problem (e.g. Figueira *et al*., 2005a; Hobbs and Meier, 2000). Typically, the differences are greater when there are more alternatives and when the alternatives have similar values for the criteria (Olson *et al*., 1995).

Since the present study is based on a previous AHP (Saaty, 1980) model development that took into consideration the opinions of the different stakeholders mentioned in Section 3.1 (Brunetti, 2007), it is particularly interesting to analyze the results obtained from the application of the Choquet integral and the solution arising from the application of the weighted sum rule on which the AHP model is based. The weighted average rule is known as one of the easiest and most familiar aggregation rules used in multicriteria analysis but, unfortunately, it does not allow to take into account interactions between criteria and can therefore induce measurement biases.

Table VIII shows the final results for the case study under analysis arising from the Choquet integral and from the weighted average.

By analyzing the results illustrated in Table VIII, it is possible to notice that both the methodologies agree in considering the 'ecological network' the most sustainable solution for the reuse of the abandoned quarry and the 'basic reclamation' the least sustainable one. There is, however, an inversion in the ranking of the alternatives for the 'valuable forest' and the 'wetland' solutions according to the two methodologies, although the final priorities of the two alternatives are very similar in the application based on the AHP. Moreover, it is possible to say that the computation by means of the Choquet integral allows a better differentiation between the 'valuable forest' and the 'wetland' alternatives because of the possibility of taking into account the positive interaction that exists between social and environmental aspects.

The analysis thus highlights the coherence of the results obtained with the two methodologies and confirms the general trend studied by Huang *et al.* (2011) according to which, even though application of different MCDA methods to the same problem could result in different prioritization of management alternatives, in general, the top few alternatives are the same no matter which MCDA method is used. This confirms a mathematical phenomenon (e.g. explored in Triantaphyllou, 2000 and Keisler, 2008), whereby the top alternative (or group of alternatives) is often superior enough that the finer distinctions between methods are not large enough to substantially change rankings.

When such robustness is present, DMs may select methods based on considerations such as ease of use, familiarity, effect on group dynamics and likely user acceptance of results.

Following this reasoning, it is worth noticing that in the present application, despite the top ranking alternatives remain the same for the two methods, the experimentation of the Choquet integral approach has allowed to better differentiate the final priorities of the different options.

4.3. ANDNESS and ORNESS profiles

In order to analyze the compensative level of the stakeholders in the evaluation of sustainability criteria, it is possible to calculate two complementary indices, ORNESS and ANDNESS, which provide information about the pessimistic or optimistic behaviour of the respondents.

The measures of ORNESS and ANDNESS index are defined in Equations (6) and (7) as (Dujmovic, 1974; Yager, 1988):

$$\mathrm{ORNESS}(i) = \frac{1}{n-1}\sum_{T\subseteq N}\frac{n-t}{t+1}a_T \qquad (6)$$

$$\mathrm{ANDNESS}(i) = 1 - \mathrm{ORNESS}(i) \qquad (7)$$

where a_T is given by the Mobius transform (Grabisch *et al*., 2003) as represented in Equation (2).

Table VIII. Analysis of the Choquet integral and the weighted sum results

Alternatives	Priorities according to the Choquet integral	Priorities according to the weighted sum rule
Basic reclamation	381.793	97.237
Valuable forest	597.260	218.217
Wetland	682.345	210.086
Ecological network	852.930	283.521
Multifunctional area	436.170	191.493

The measures can be interpreted in the context of well-established behavioural theory of decision making (March and Shapira, 1987; Bodily, 1985). According to this theory, an essential component of any decision-making process is the attitude of the DM towards risk. An individual with low risk-taking propensity will typically weigh negative outcomes more highly and, on the contrary, an individual with high risk-taking propensity is more likely to weigh positive judgments more highly. Accordingly, ORNESS can be recognized as a measure of the degree of the DM's optimism (Yager, 1988). The index value ranges from 0 to 1. The values of ORNESS in the range from 0.5 to 1 represent optimistic decision strategies, a compensative profile, whereas the values less than 0.5 represent pessimism decision strategies, a noncompensative profile.

ANDNESS and ORNESS indices play a fundamental role in the evaluation models in the domain of sustainability assessment, because they permit to understand how much the compensation among the different dimensions is allowed in the opinion of the DM.

In the case of the present application, it is possible to say that ANDNESS and ORNESS indices take the following significance (Giove *et al*., 2011):

- ANDNESS = 1 and ORNESS = 0: the experts consider that for a project to be sustainable, it must satisfy all the considered dimensions (namely, environmental, economic, institutional and social aspects). This is the case of the totally noncompensative profile;
- ANDNESS = 0 and ORNESS = 1: the experts consider that for a project to be sustainable, it has to satisfy one of the considered dimensions. This is the case of the totally compensative profile;
- ANDNESS > 0.5 and ORNESS < 0.5: the experts consider that for a project to be sustainable, it has to satisfy the most part of the considered dimensions;
- ANDNESS < 0.5 and ORNESS > 0.5: the experts consider that for a project to be sustainable, it has to satisfy one dimension rather than another;
- ANDNESS = 0.5 and ORNESS = 0.5: the experts consider that the sustainability of a project depends on the sum of the scores of the considered dimensions, without taking into account the presence of synergies among them.

In the present research, the calculation of the ORNESS index shows a quite optimistic behaviour of the stakeholders who tend to be satisfied if only one criteria is good; in fact, the average of the index calculated for each real actors involved in the evaluation process is 0.54. Figure 7 shows the result obtained in the calculation of the ORNESS index.

5. CONCLUSIONS

The paper illustrates the application of an evaluation model based on the Choquet integral approach and on the data coming from a system of sustainability indicators, to rank different possibilities for the reuse of an abandoned open-pit quarry in Northern Italy.

The results of the performed analysis show that the proposed model is suitable to represent the real problems of a territorial system and the complexity of the decision under examination, leading towards an integrated assessment. Although the adopted methodology is complex and requires conceptual efforts and elaborated data collection and computations, it provides a synthetic measure of sustainability and easily comparable solutions. This application represents thus a test case for studying the usefulness of the proposed method in the evaluation of the interaction between criteria, which seems to be an interesting research issue in the field of sustainability assessments.

Furthermore, the performed analysis provides a robust and transparent decision-making structure, making explicit key considerations and values and providing opportunities for stakeholders and community participation (Munda, 2005).

The procedure followed in the application seems to be suitable for dealing with real world problems from

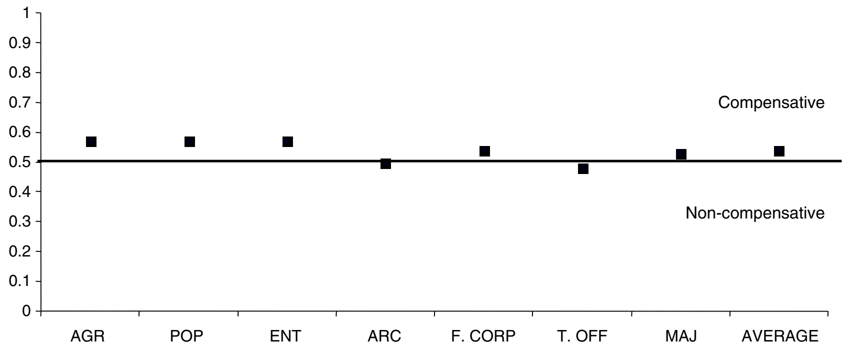

Figure 7. The ORNESS index for the case under examination.

a practical point of view, showing a way for considering the whole range of available information and for taking into account experts opinions. Moreover, the results are precise and easy to be interpreted and communicated.

However, there are still several opportunities for expanding the study and for validating the obtained results. The most important developments of the work concern (i) the construction of the utility functions used in the evaluation; and (ii) the definition of the capacity. More specifically, future developments of the study refer to the exploration of other value functions construction approaches in order to improve the model and to validate the obtained results, by addressing also the commensurability issue among criteria. Moreover, in order to validate the application of the Choquet integral in real decision problems, it would be of scientific interest to perform the evaluation through the 2-additive Choquet integral with a computation of the importance indices and the interaction indices, searching for an interpretation from the DM's standpoint.

Further developments of the application would also consider the exploration of other domains of research. In this sense, it would be important to investigate the representation of the interactions among the criteria through the extension of the comprehensive (overall) concordance index of ELECTRE methods as proposed by Figueria *et al*. (2009). Secondly, additional validation could be explored by means of the application of the non-additive robust ordinal regression (Angilella *et al*., 2010), which explicits positive and negative interactions among criteria starting from the evaluation of the alternatives. Thirdly, given the spatial nature of the decision problem under analysis, future improvements of the work will also refer to the integration of the MCDA tool with geographic information systems (GIS) in order to develop a multicriteria spatial decision support systems that will enable multipurpose planning. In this sense, visualization techniques are of major importance in presenting and communicating the results to DMs and the interest groups (Malczewski, 1999; Ferretti, 2011). Moreover, it would be of scientific interest to test the model through sensitivity and robustness analysis and to investigate dedicated software for the computational process. Finally, the investigation of the degree of compensability among the criteria could be explored by means of different approaches, following the reasoning proposed in Vansnick (1986).

In conclusion, the application of the Choquet integral constitutes a very promising research line in the field sustainability assessments of territorial transformation projects where trade-offs and interactivity exist among the conflicting aspects involved in the decision.

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