Multi-criteria analysis for the assessment of the environmental and social impacts of hydropower plants: twenty years of history and some recent developments

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Introduction

The reduction to bare figures of the complexity of the environmental and social aspects and impacts connected to the construction and operation of an hydropower plant (with a special focus on small hydro power plants) have never had great success up to now among the stakeholders involved in the evaluation of such outcomes.

In the paper, once described the main features of the method, in terms of criteria chosen for the evaluation (with a particular regard for the the habitat indicators based on the MesoHabSim method) a detailed analysis is carried out on the application of the proposed Multi-Criteria Analysis (MCA) to a specific case study (a 2.5 MW medium head HP plant) underlining strengths and weaknesses; in the end some suggestions for possible improvements are proposed as well.

1. About multi-criteria analysis

Multi-criteria analysis (MCA) or, more precisely, concordance analysis, evaluates the outcomes of a given set of alternatives in terms of multiple decision criteria simultaneously applied. For each alternative project or scenario it must be possible to obtain a measure of its effects in terms of each individual criterion considered.
To avoid any kind of arbitrary evaluation, such measures should generally be quantitative.
However, for certain aspects that could be difficult to quantify, the method also admits measures of a qualitative nature, which may be expressed through appropriate point-scores: nevertheless the use of measurable criteria is strongly recommended.
In either case, the measure of each effect must be determined prior to performing concordance analysis.
Back almost twenty years ago, in the frame of an international project supported by the European Commission, a numerical tool based on the principles and algorithms of the Multi-Criteria-Analysis (MCA) was implemented in order to supply a mean as objective as possible to carry out Environmental Impact Assessment, based on objective criteria linked to measurable quantities - energy, velocities, areas, volumes and so on - in order to avoid any unacceptable arbitrary or too subjective evaluation.
Strange to say, the adoption of MCA as a common tool had little success mainly for the alleged excessive objectivity and also for the difficulty of finding shared criteria of evaluation among decision makers.

2. Allein HPP case study

More recently, thanks to the direct involvement of environmental public agencies in assessment procedures, MCA method has been officially adopted in the Autonomous Region of Valle d'Aosta (Northern Italy) to evaluate the effects of different alternatives of ecological flow releases downstream of existing weirs and dams of hydropower plants and of new plants as well.
Far from being envisaged as an automatic tool for decision making, nevertheless the method is built in order to provide a common platform to increase the quality of decision making about a subject source of many disputes among agencies, investors and other stakeholders.

2.1 Description of the plant

The hydropower plant of Allein diverts water from the Artanavaz stream by a fixed weir with lateral intake, followed by a small basin and a steel penstock (with diameter 1,40 m and length approx. 1.100 m) leading to the powerhouse, which hosts two horizontal Francis turbines, directly coupled to synchronous generators.
The main features of the plant are the following:

- maximum diverted flow rate 3.10 m^3/s
- yearly average flow rate 1.58 m^3/s
- nominal (gross) head 98.49 m
- nominal (~average) power 1,523.70 kW
- rated capacity 2.5 MW

At the beginning of 2016 Cooperative Society *Forza & Luce Aosta*, the Owner and Operator of the plant, started a 5 years experimentation, agreed with the administration, environmental protection agency and fishery support consortium of the Region, aimed at determining the quantity of reserved flow to be released and monitoring the ecological effects on the stream of the envisaged increase (from 2.0 to the abovementioned 3.1 m^3/s) of the maximum flow rate diverted by the plant.
During each of the 5 years of experimentation, different scenarios of reserved flow release (both fixed and variable on a monthly basis) will be assessed with respect to the economic and environmental aspects.
So at the end of 2020, on the basis of the experimentation outcomes, the regional administration will decide whether to confirm or not the increased maximum flow diverted by the plant and will establish the quantity and possible time modulation of the reserved flow to be released at the intake works.

Fig. 1. Position of Valle d'Aosta Region in Northern Italy, with the red dot representing the plant location.

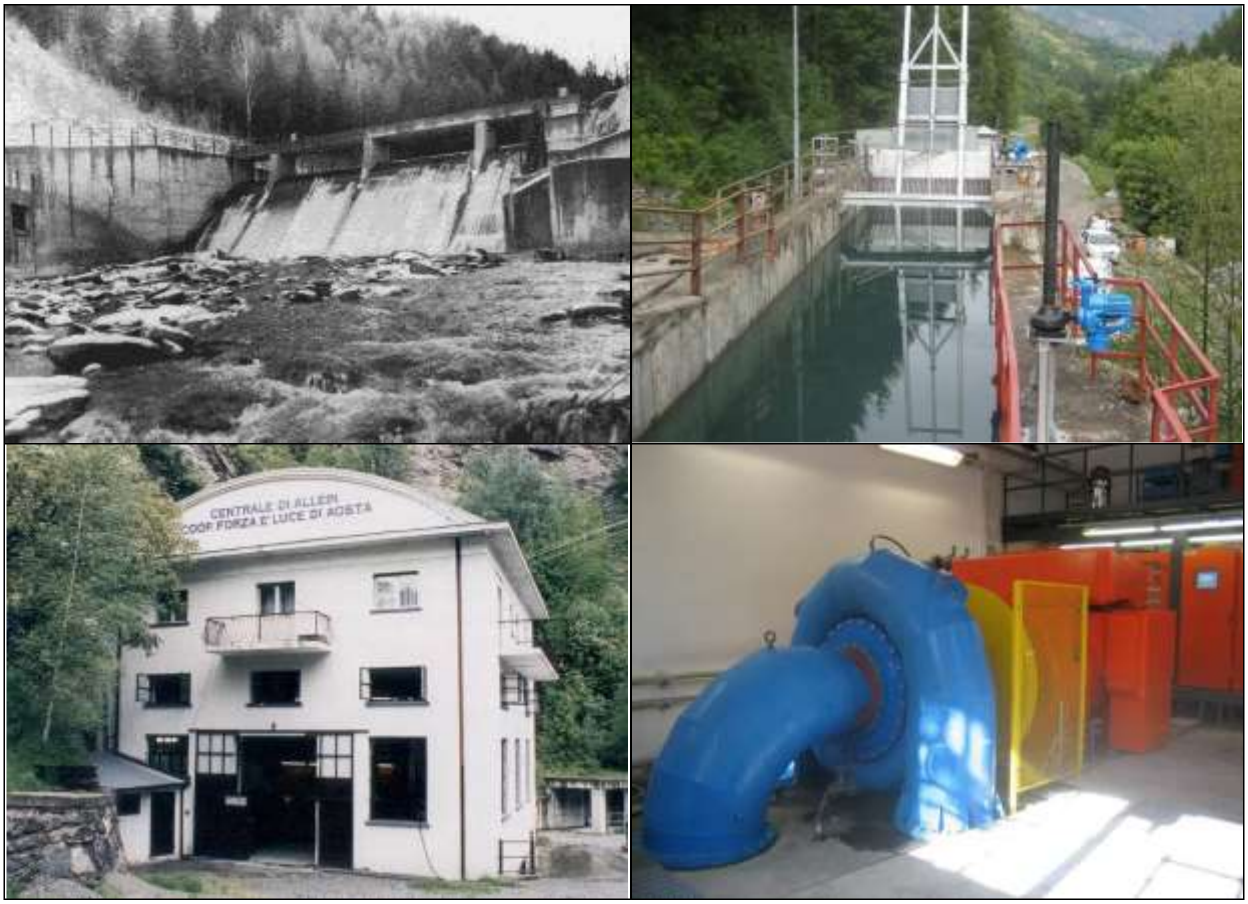


Fig. 2. Diversion weir, forebay, powerhouse and generating unit of Allein HPP

2.2 MesoHabSim

The MCA adopted in Valle d'Aosta largely relies on the MesoHabSim method to evaluate the environmental outcome of an alternative project or scenario.

In particular this method, as suggested by the complete name *Mesohabitat simulation model*, is designed to predict the response of an aquatic community to its habitat modifications; basically the changing spatial distributions of physical attributes of a river as a result of variations in flow and the biological responses of aquatic species to these changes provide the basis for simulating the consequences of ecosystem alteration.

MesoHabSim, created at the beginning of this century by Dr. Piotr Parasiewicz, builds upon pre-existing physical habitat simulation models, such as the PHABSIM, and modifies their data acquisition technique and analytical approach by changing the scale of resolution from micro-scale to meso-scale. Due to this increase in scale, the model takes into account variations in stream morphology along the river and allows for application in larger-scale projects. Habitat and fish measurements at larger spatial units are more practical, more relevant to river management and more favourable to habitat modelling.

Summarising the procedure:

- mesohabitat types are defined by their hydromorphological units (HMUs) such as pools and rapids, geomorphology, land cover and other hydrological characteristics;
- mesohabitats are mapped under multiple flow conditions at extensive sites along the river;
- fish or invertebrate data is collected in randomly distributed mesohabitats where habitat surveys are also conducted;
- this data is used for developing mathematical models that describe which mesohabitats are used by animals more frequently;

- this allows for evaluating habitat availability at a range of flows, expressed by rating curves, which represent the changes in a relative area of suitable habitat in response to flow and allow for the determination of habitat quantity at any given flow within the range of surveys. Rating curves can also be used to evaluate the benefits of various restoration measures on the entire fish community, both for the entire river and for specific sections;
- in combination with hydrologic time series, rating curves are used to create Uniform Continuous-Under-Threshold (UCUT) curves for the analysis of frequency, magnitude and duration of significant habitat events. UCUT curves evaluate continuous durations of unsuitable habitat under a specified threshold. UCUT curves serve as a basis for the development of "ACTograms", diagrams representing graphically the activity and response of the target species to habitat changes such as flow reductions, that managers can use to determine how long a given species can tolerate unsuitable conditions depending on its life stage.

MesoHABSIM is designed to assess habitat availability not only for individual species but also for an entire aquatic community to analyse and predict ecosystem potential. In this case a comprehensive list of species is generated from literature sources and available regional data collected on relatively intact river reaches. The species are ranked on the basis of abundance in the long-term fish collection data from multiple rivers of similar character and expected proportions of each species are calculated. Since community structure may change seasonally, for each season (bio-period) a number of indicator species is selected, for which a habitat model is developed.

The results of MesoHABSIM create the framework for integrative analyses of many aspects of the ecosystem.
It also allows managers to recreate reference habitat conditions and evaluate possible instream and watershed restoration measures or alterations, such as dam removals or changes in water withdrawals.
From the perspective of resource managers, it not only allows for quantitative measures of ecological integrity, but also creates a basis for decisions where trade-offs between resource use and river restoration need to be considered.

The principal benefits of the MesoHabSim method are the following:

- it offers flexibility, open architecture and effective simulation capabilities thanks to its GIS framework;
- it is designed to address habitat needs of entire aquatic communities (fish and micro-invertebrates) and it operates at the meso-scale, that's more relevant for river management and less affected than micro-scale by coincidence in snap-shot observations in the validation phase;
- the model is established on a solid ecological background but its outputs are designed to be comprehendible and convincing to non-scientists;
- it offers a quantitative assessment and produces quantitative restoration endpoints;
- it offers the ability for trade-offs between habitat structure and flow quantity.

2.3 SESAMO

SESAMO is a decision support method developed in the framework of the European programme SPARE (Strategic Planning for Alpine Rivers Ecosystems) and based on the MCA methodology, that allows the user to manipulate also graphically all the objects - criteria and alternatives, utility functions and weights - in order to get the final ranking of the alternatives and to analyse the composition of the results, performing sensitivity analyses as well.
Specific panels in the graphical interface of the software represent all the 7 phases of a MCA decisional process:

1. organisation of criteria in a decision tree;
2. filling evaluation matrix with alternatives;
3. application of technical aggregation;
4. application of utility functions;
5. allocation of weights;
6. final ranking;
7. sensitivity analysis.

SESAMO operates on projects. A project is an independent entity that contains all the data and structures that are related to the description of a decision-making process applied to a specific problem.
It is possible to associate documentation to each object in the project. Through documentation, the user can enter text useful for understanding all the operations that he/she is performing on a specific node of the decision tree.

In the end it's worth reminding that SESAMO has been developed to assess and compare alternative scenarios of reserved flow release; therefore, even if its structure is flexible and can be applied practically to any cost-benefit analysis, the indicators illustrated below (mainly nondimensional, except where otherwise specified) are referred to the trade-off between economic and environmental issues.

2.4 MCA: Allein HPP case study

The MCA application in the case of Allein is aimed at defining the optimum quantity and modulation of the reserved flow to be released in the Artanavaz stream downstream of the plant intake works.

The alternatives scenarios analysed for Allein HPP are the following:

0. no release (theoretical scenario, only for comparison)
1. modulated release (in the range 250 - 500 l/s) on a monthly basis
2. 280 l/s fixed release
3. 350 l/s fixed release
4. 250 l/s fixed release + 10% of the instantaneous river flow

The analysed indicators for each scenario are listed and classified as follows

Energetic

- IEn = energetic index, representing the percentage loss of energy production with respect to the theoretical scenario of no release and maximum production.

Economic

- IEc = economic index, representing the percentage loss of income with respect to the theoretical scenario of no release and maximum production and income
- NPV = net present value [€] of the scenario
- PBP = payback period [years]
- LCOE = levelized cost of energy, i.e. unit cost [€/MWh] of the energy over the life cycle of the plant, or in this case over the 30 years duration of the water concession right
- CD-BIM-SER = acronyms for various fees and levies related to the water concession
- RCS-REC = social and economic repercussions (environmental monitoring and management, road maintenance, supply of services, royalties and taxes) of the plant operation on the community.

Environmental

- IH = habitat integrity index, which quantifies the available area for fish fauna according to the MesoHabSim method, divided in 5 main steps
    1. identification of the stretch to be analysed, according to its morphology, hydraulic features (flows, slopes...) and riverbed sediment;
    2. choice of the hydrologic conditions (at least 4 with different flow rates) for the execution of the hydro-morphologic surveys;
    3. description of the riverine habitat in different hydrologic conditions, through a (georeferenced) 3D survey of the points representing the wetted perimeter and characterisation of the mesohabitat, by means of many variables (river flow rate, water surface slope, longitudinal connectivity, presence of shadow and cover...) whose values can be stored and represented on GIS software;
    4. application of the biologic models of habitat adequacy, with respect to the target fish species and the relevant statistic models evaluating the probability of presence and abundance on the basis of the surveyed parameters;
    5. analysis of the time and space variations of the riverine habitat.

    IH is equal to **0** for the maximum negative effect of the water diversion on the hydro-morphologic components river and increases up to **1** (no impact) for decreasing negative effects.

Landscape

- TP = landscape protection level, representing the modifications of the landscape perception related to the quantity of water in the diverted stretch. This indicator is an evolution of the "Tyrol landscape indicator" developed by the University of Innsbruck, modified to account for the context (natural, environmental and cultural emergencies, laws and constraints, etc.) of the Valle d'Aosta Region. Its evaluation follows 3 steps:
    1. identification of homogeneous (from the point of view of visibility) stretches within the diverted reach and definition of the "constraint factor";
    2. attribution of release coefficients and relevant protection level, definition of the "release factor";
    3. analyses of pictures taken in different hydrologic conditions and definition of the "visual factor".

    For each stretch TP is equal to the sum of the three aforesaid factors.
    The final value for the diverted reach is the length-weighted average of the TP values for each stretch

Due to the peculiarity of Allein's case, with no plant construction or rehabilitation, it was agreed with the regional administration that PBP and LCOE would not be used in the MCA, because the PBP is applicable only to new or rehabilitated plants, with negative cash flows in the first years due to the initial investment, while the information content provided by the LCOE is too similar to that of the NPV.

Furthermore, it's worth pointing out another peculiarity in the application of the MCA to the case study, this time concerning the basic hydrologic data. The energetic and economic indicators are evaluated *a priori*, i.e. by inserting the alternative release scenarios in a long period Flow Duration Curve to obtain the expected energy production, then applying the (yearly average) energy selling prices and the operating costs, both recorded and provided by the plant operator. On the other hand, the landscape and environmental indicators are related to the actual flow measured in the diverted stretch, based on the variables (gate opening, diverted flow, water stages etc.) recorded hourly by the plant operator and computed according to the scheme reported in Figure 3.

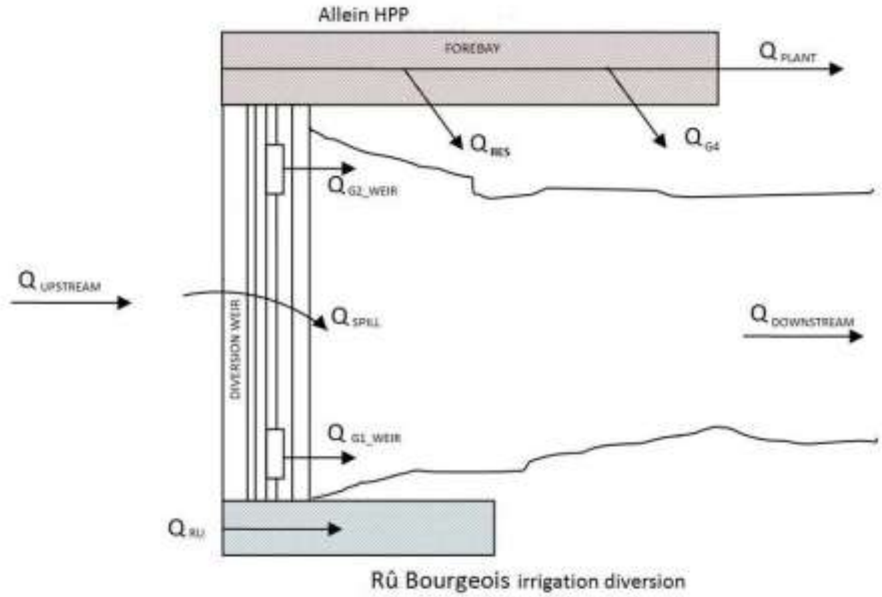


Fig. 3. Functional scheme of Allein HPP's weir and intake

Therefore the MCA for Allein HPP mixes two types of evaluation:

- hydrologically based forecast of energetic and economic indicators;
- computation of environmental parameters, related to recorded flows in the diverted river stretch.

Consequently, only after December 2020, at the end of the experimentation, it will be possible to draw conclusions on the environmental impacts and therefore on the whole MCA.

The following table shows the resulting values of the indicators for the alternative scenarios described above; the environmental and landscape indicator (IH and TP) are given hypothetical values, waiting for the definitive ones.

Values	*Alt. 0*	*Alt. 1*	*Alt. 2*	*Alt. 3*	*Alt. 4*	*u.m.*
IEn	1.00	0.85	0.88	0.84	0.76	-
IEc	1.00	0.84	0.85	0.83	0.74	-
NPV	9,611,052	8,035,694	8,213,835	8,025,227	7,147,811	€
CD	48,020	40,937	42,017	40,536	36,618	€
BIM	56,180	47,894	49,158	47,424	42,840	€
SER	10,579	9,018	9,256	8,930	8,067	€
RCS	1.00	1.00	1.00	1.00	0.80	-
REC	1.00	0.70	0.73	0.70	0.55	-
IH	0.35	0.57	0.50	0.55	0.65	-
TP	55	85	65	80	95	-

Tab. 1. Resulting values of the indicators, with the relevant units of measure (u.m.)

Then a utility function is defined, transforming the values of the parameters in a score ranging from 0 to 1 according to different rules (linear, increasing or decreasing, by steps, analytical ...) related to the nature of the indicator.

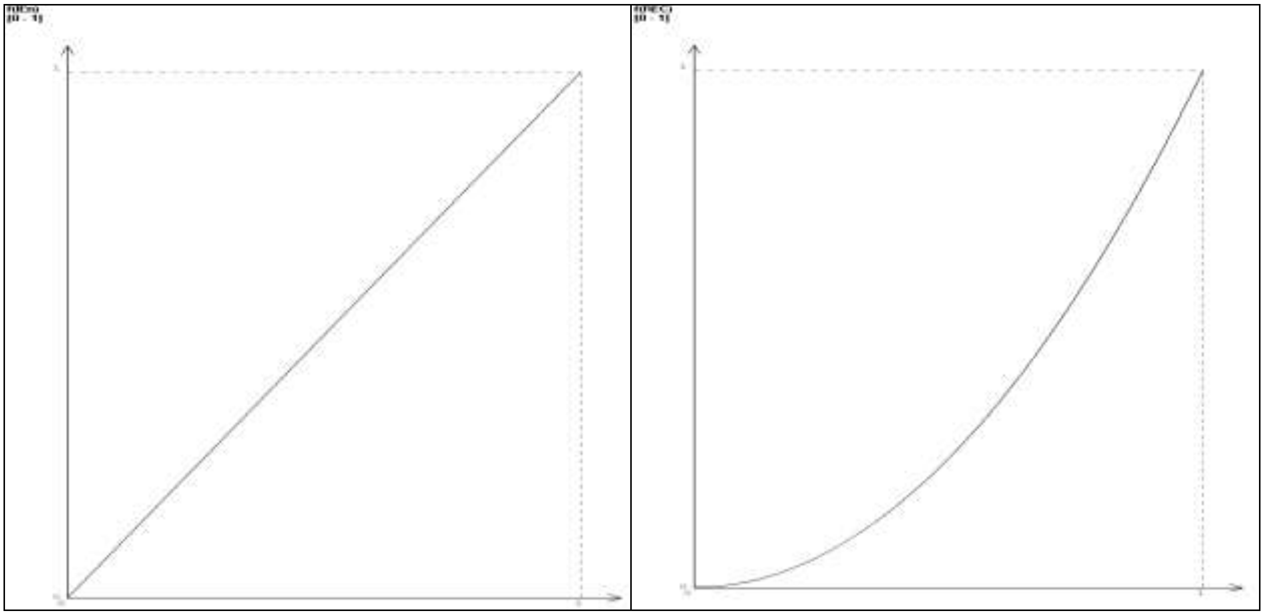
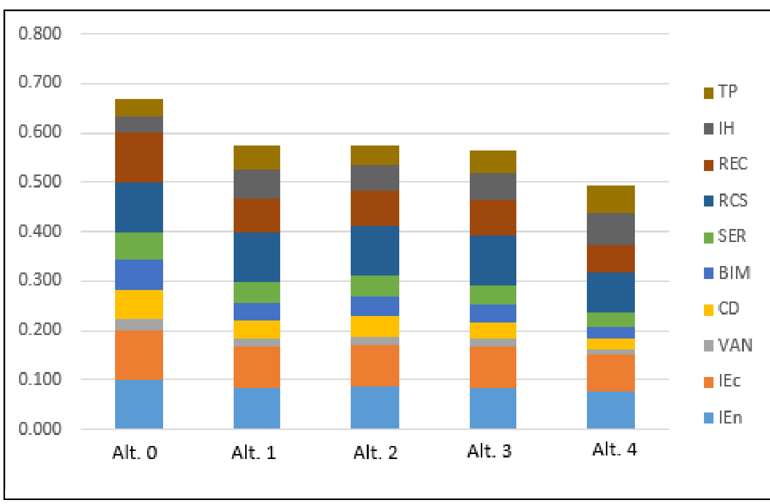


Fig. 4. Examples of utility functions of some indicators (IEc and REC) for Allein MCA

Subsequently the indicators are given weights, automatically normalised by the software, representing their relative importance, then the weighted sum of the indicators' scores gives the final score of each alternative and consequently its ranking.

Figure 5 represents the results obtained with:

- equal weights $w_i = i/N = 0.10$ for all the indicators;
- utility functions defined in the guidelines [**1**] developed within the SPARE programme for MCA;
- hypothetical values (see Table 1) assumed for IH and TP.



Ranking	*Score*
Alt. 0	0.668
Alt. 2	0.582
Alt. 3	0.579
Alt. 4	0.567
Alt. 5	0.498

Fig. 5. Composition of the results and final scores for the alternative scenarios

Moreover, as previously said, SESAMO allows to perform - with an intuitive graphical interface - an analysis of the correlation and sensitivity of results with the indicators.

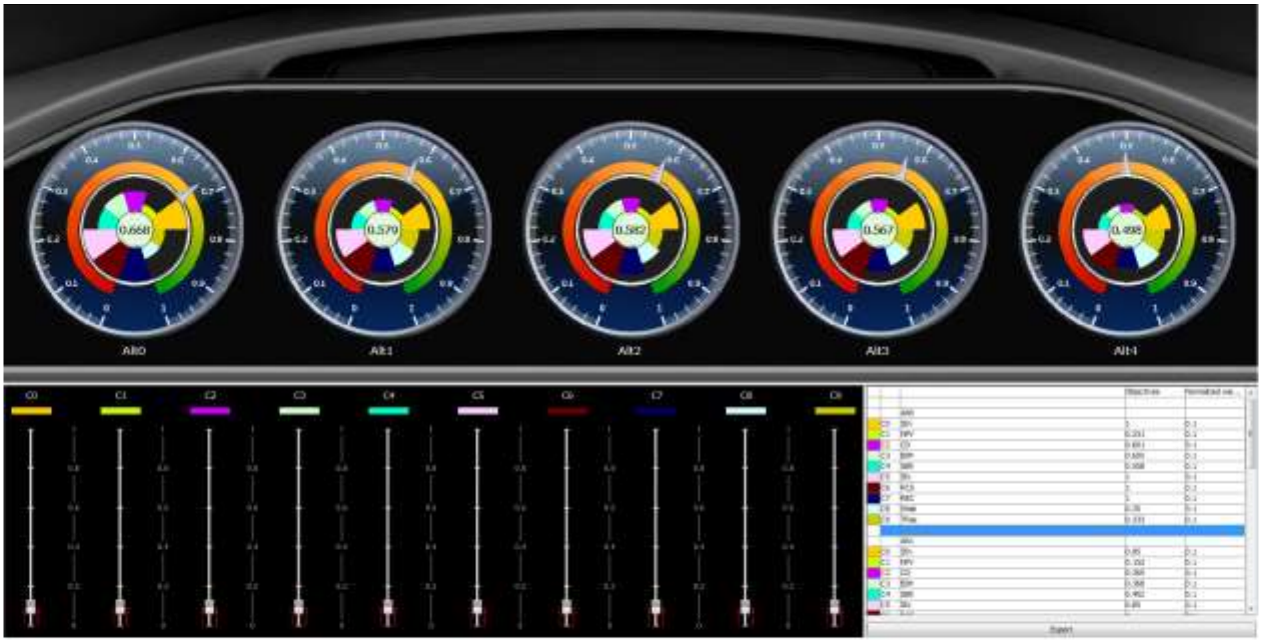
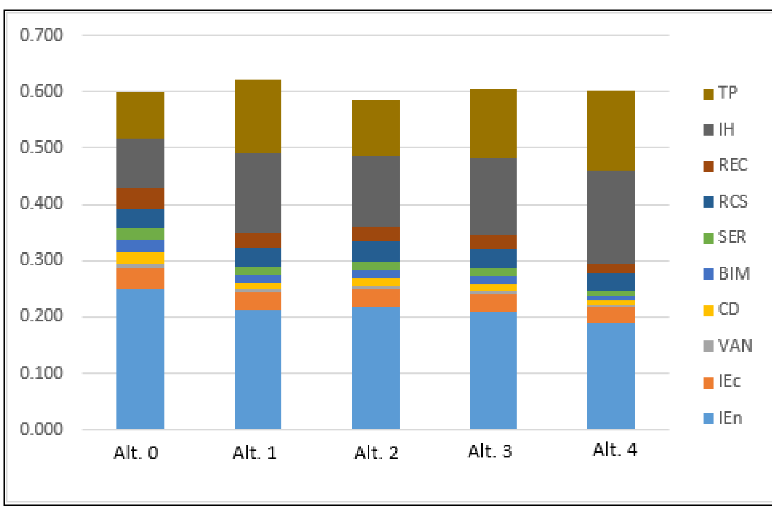


Fig. 6. Interface for the correlation and sensitivity analysis in SESAMO

Weights still have to be discussed and agreed with the regional administration and the other involved authorities. Moreover we'll be able to have the specialists' assessment of the environmental and landscape indicators only at the end of the experimentation.

The following figures show an example of alternative weighing of indicators, with a weight of 0.25 for each category (energetic, economic, environmental and landscape) of indicators, so the single economic indicators have a much smaller weight.
The resulting alternative ranking is quite different from the previous.



Ranking	*Score*
Alt. 1	0.621
Alt. 3	0.605
Alt. 4	0.603
Alt. 0	0.599
Alt. 2	0.584

Fig. 7. Composition of the results and final scores for the alternative scenarios

In conclusion the results illustrated in this paper represent a first output and a basis for further discussions with the other stakeholders and authorities involved in the experimentation.

4 Conclusions

In the end, the MCA carried out with SESAMO seems a promisingly simple and user-friendly tool, clearly showing the composition of results and the effects of the chosen indicators and relevant weights on the final results.

A few remarks arise from the elaborations carried out so far:

- the economic indicators are more than the others, but some of them represent the economic repercussions on the community, while other ones represent the repercussions on the plant owner and operator;
- RCS and REC are quite difficult to evaluate and in this case they have been computed in a simplified way, as suggested by the guidelines [**1**] developed within the SPARE programme for the definition of indicators relevant to MCA of alternative reserved flow scenarios;
- the environmental and landscape indicators need expert judgement; in particular IH is computed with a long (compared to other indicators) technical procedure, while the evaluation of TP is quite subjective, especially in the last of the three steps described earlier in this paper;
- it's important to have also high flow recorded, in order to evaluate the environmental indicator IH with the MesoHabSim methodology in a "balanced" way, that is not too unfavourable and punitive for hydropower production.

Possible improvements of the procedure - to be discussed and agreed with the other stakeholders - may concern the evaluation of RCS and REC and the subjectivity of the experts' assessment of TP.
The attribution of indicators' weights will be a hot topic as well.

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