Participatory decision making in reservoir planning

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Abstract: The technologies and methods for integrated planning and management of water resource systems have matured considerably over the past decades. However, relatively few of them have been actually and regularly applied in real world decisional processes. We feel this is essentially due to a general lack of engagement of stakeholders and decision makers at every stage of the decisional process. Innovative methodologies and tools to improve participation are presented, with focus on water reservoir systems.

1 INTRODUCTION

It is very probable that the century we have just entered will be remembered as the "century of water", since water will be by far the scarcest resource, the availability of which will constrain the economy of nations. In the last fifty years water demand in the world has trebled and is still increasing sharply every year as a result of population growth, increase in household income, and irrigation development. Approximatively 70% of surface water and groundwater is claimed by irrigated agriculture, to produce 40% of worldwide food needs (Brown [2001]). Even though demand for water is increasing, rare are the countries in which its availability remains constant; more frequently the exploitation is well beyond the renewal rate of the resource. Degrading water quality further reduces the availability of freshwater suitable for domestic and agriculture use and increases the cost of treatment and reuse of water. Driven by these challenges, the last years have seen a wide and growing interest towards the development of tools and techniques for integrated planning and management of these systems (see for example SFWMG [1987]; Simonovic and Savic [1989]; Loucks [1990]). While in the 1960's the planning was based on the assumption that water was an infinite resource and the main concern was its allocation and distribution, now the approach must be oriented to sustainability and must be more holistic.

Nonetheless technology alone is not enough, if the projects that it suggests actually remain unrealized: in fact the accomplishment is quite often politically thwarted by the disagreement of all the stakeholders that are excluded by the benefits or that fear damage from the proposed actions. To overcome this risk it is essential to assess in detail the likely impacts of a project not only on those objectives for which it has been conceived and designed, but also on all the sectors that it may influence. The human role in the decisional process must be supported and valued by exploiting the power of models to determine the effects of alternative projects with low cost and low impact computer-based experiments. The selected course of action should emerge out of a debate, that involves the participation of all the stakeholders. To reach this goal a formalized planning procedure was required, a procedure that guarantees to determine a solution that is equitable, efficient and sustainable: the so called Environmental Impact Assessment (EIA) procedure emerged as the most appropriate. Indeed in the last decades many countries have enacted legal frameworks for EIA, by specifying rules, methodologies and guidelines for its application in different planning situations.

Water resources systems we will refer to in this paper are storage systems, composed of multipurpose reservoirs or regulated natural lake, catchments, channels, rivers, streams, water users, etc., all of them interconnected by the downstream flow of water. Water supply for agriculture and power generation are usually considered the two main purposes of such systems; however the water collected by these facilities may serve several other scope, such as navigation, recreation, flood protection, downstream river quality conservation, etc. Hence any decision taken on these systems directly or indirectly involves a wide range of stakeholders.

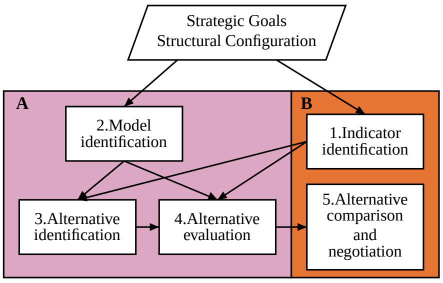

Figure 1: The EIA procedure scheme.

2 EIA PROCEDURE

The EIA procedure can be formalized for these systems as the five-stage process outlined in Figure 1. The scheme draws a conceptual map of phases to be followed by the system analyst (SA). More in detail, given a structural configuration of the system (existing or proposed) and on the basis of the strategic goals pursued, the SA should elaborate and compare alternative planning proposals with the following procedure:

1. *Indicator specification*: the strategic goals are translated into operational criteria and the latter into physical and economical indicators, which can be then quantitatively computed. For example the indicators may evaluate the performances in supplying water to civil, agricultural and industrial users, the compliance to river quality standards, and flood control targets. Since the operational criteria reflect concerns and priorities of the stakeholders, they should be defined by interacting with them.

2. *Model identification*: the components (catchments, reservoirs, channels, water users, etc.) associated with a given structural configuration of the water system are described by mathematical models. The choice of these models as well as the degree of detail depends on both the selected indicators and the alternatives to be evaluated, thus there exists a recursion among this phase and phase 1 and phase 3.

3. *Alternative identification*: all the feasible structural and/or normative actions are first quantified and then combined in all possible way. Each combination constitutes a planning alternative.

4. *Alternative evaluation*: for each alternative the values of the indicators are assessed by simulating the behavior of the system.

5. *Alternative comparison and negotiation*: the preference systems of the stakeholders are identified. Then, the alternative proposals are compared according to multi-attribute and negotiation aid techniques. Finally, a sensitivity analysis is performed to check the robustness of the ranking with respect to the uncertain and subjective elements. All these actions help the decision maker (DM) to select a compromise decision.

The practical application of the above procedure poses two fundamental concerns: first, the SA should widely interact with all stakeholders during the phases of indicator specification, model identification and alternative evaluation; second, the information used at each stage should be obtainable from the previous stages and made available for the successive. More in detail this information must be complete, shared, transparent, easily obtainable, well structured and flexible. The problem is further complicated by the non-strictly serial succession of stages and by the diffuse presence of recursions. Hence the effective implementation of the above scheme requires the support of a computer-based system, a Decision Support System, which provides the tools to integrates all the phases in a unique framework, facilitates participation, and ensures that the information has the above mentioned properties.

The proposed EIA scheme is a procedure of general validity. It has been originally introduced for a delimited class of problems, but it may be applied to a broad range of planning contexts. Its use for water system planning poses several challenging and significant issues. In this paper we will analyze four of them and propose for each one some innovative approach. We will conclude the paper by presenting the architecture of a DSS which satisfies the above mentioned requirements and imbeds the innovative proposals.

3 DYNAMIC AND CONTROL

EIA analysis as well as the Multi-Attribute Value Theory (MAVT) (Keeney and Raiffa [1976]), upon which it is based, have been traditionally developed and are usually adopted to evaluate projects on static systems (or systems that are assumed to be static for modelling reasons). Then they implicitly consider

Figure 2: The lake Verbano water system and the two irrigation districts.

decisions as *planning actions*, that is *una tantum* decisions, that permanently modify the system configuration. This way of doing does not lend itself to the intrinsically dynamic nature of water reservoir systems. To better clarify this issue consider as example the Verbano water system (see Figure 2), located on the italian-swiss border (Soncini-Sessa et al. [2000]). Its storage is primarily used to provide water supply to two wide irrigation districts and several hydropower plants, but it also influences a plethora of other socio-economical and environmental factors (lacustrine and riverine water quality, upstream and downstream flood control, lacustrine navigation and tourism, and so on). Obviously the volume of water stored in the lake (i.e. the state of the system) is time-variant. At each time instant (i.e. every morning) the DM must decide how much water has to be released in the next 24 hours. Clearly the volume of water that can be released depends on the volume of water currently available into the the lake. The release decision influences the lake storage of the next day and hence influences the next release decision. Decisions are thus concatenated after each other and recursive, that is they are *management actions*. These actions can be formulated in a rational way by designing a *management policy* (see definition in the next paragraph), the choice of which can conceptually be included in the EIA at the same level of the other planning actions. Straightforwardly a planning alternative is constituted by a triple: structural actions (i.e., dredging of the lake outlet), normative actions (i.e., review of the regulation range and imposition of a minimum instream flow) and one management policy. The identification of the alternative in phase 3 should therefore include the "quantification", i.e. the design, of the management policies too.

3.1 The management policy

It's time to give a more formal insights on management policies. We will make reference to the Verbano case to be less abstract. Known the current lake storage s_t at time step t, the release decision u_t is given by:

$$u_t = m_t(s_t) \tag{1}$$

where $m_{\cdot}(\cdot)$ is a succession, generally periodic of period T, of monotone non-decreasing functions of s_t, named *control laws*. A management policy p is a succession $[m_0(\cdot), m_1(\cdot), ..., m_{T-1}(\cdot), ...]$ of control laws. Given a couple of structural and normative actions a management policy is synthesized by solving an optimal control problem, defined as:

$$\min_p \lim_{t\to\infty} Crit_{\varepsilon_1,\ldots\varepsilon_{t+1}} \left[\sum_{i=0}^{n} \lambda_i Z_i(p) \right] \tag{2a}$$

$$Z_i(p) = \sum_{\tau=0}^{t} g_\tau^i(s_\tau, u_\tau, \varepsilon_{\tau+1}) \tag{2b}$$

$$s_{t+1} = f_t(s_t, u_t, \varepsilon_{t+1}) \tag{2c}$$

$$u_t \in U_t(s_t) \tag{2d}$$

$$\varepsilon_{t+1} \sim \phi_t(\varepsilon_{t+1}|s_t, u_t) \tag{2e}$$

$$u_t = m_t(s_t) \tag{2f}$$

$$p = [m_0(\cdot), m_1(\cdot), ..., m_{T-1}(\cdot)] \tag{2g}$$

where all the functions are periodic of period T. The weights λ_i $(i = 1, ..., n)$ expresses the relative importance of n indicators $Z_i(p)$, chosen among the ones identified in phase 1, each one of which is the sum over time of step costs $g_t^i(\cdot)$. The set $U_t(s_t)$ is the set of feasible controls (that may vary with the storage s_t); $\phi_t(\varepsilon_{t+1}|s_t, u_t)$ is the conditional probability distribution of the disturbance ε_{t+1} (e.g. the inflow to the lake) and $Crit$ is a suitable criterion (i.e a statistic) to filter the disturbance (see Yakowitz [1982] and Soncini-Sessa et al. [1991]). The structural-normative actions are embedded in the constraints (2c), (2d) of the control problem. Thus, given a pair of structural-normative actions, several (theoretically infinite) different management policies can be devised, by varying the weights λ_i. The set of these policies constitutes the Pareto boundary of the problem, that is the set of non-dominated policies with respect to the management objectives.

When the water system is more complex than the Verbano water system (e.g. it has more reservoirs), its state is a vector x_t, that contains the states of all the dynamical components within the system. Then the management policy can be synthesized by a problem analogous to problem (2), where s_t is substituted by x_t and u_t is the vector of all the decisions that must be daily assumed in the system.

3.2 A two-level decision approach

The analysis of the decisional organization of a Water Agency leads towards the idea of a multi-level DSS. In fact, in a Water Agency, one can usefully distinguish different levels of decision making. Anthony [1965] considers three levels: *strategic planning*, *management control*, and *operational control* (denoted in the following simply as planning, management and control)(see Figure 3). The planning level has to do with the strategic goals to be pursued in the system management and with the ways to achieve them: management policies are designed at this level. The policies set up at the planning level can be expressed either by closed form rules, resulting from the solution of off-line optimal control problems, or by on-line optimal control schemes. The scope of the management level is the utilization of the resources in an effective way in the short and medium term, according to the directive issued by the planning level and to the particular situation the DM is facing (e.g. the out of order of a power plant). This is the level were the man-machine interaction is more tight and where conflicts are likely to arise. The control level has to implement the management decisions in the real time operation and it is generally highly structured, so that fixed rules can be applied. Thus, the control level is served by a controller, while the other two levels need two separate DSSs: DSS/M and DSS/P where M stands for management and P for planning. The planning module DSS/P deals with the choice of the alternatives and its outputs are planning decisions, management policies, and models. All of them constitute inputs of the management module DSS/M. The interaction among the SA, the DM, and third parties (stakeholders) takes place in the DSS/P at the planning level and in the DSS/M at the management level. The scheme of Figure 1 can be embedded in this two-level structure, thus obtaining the scheme in Figure 4.

The two-level structure embodies an interesting skill: the planning tools are naturally and unexpensively updated. In the usual planning approach, once the planning action is over, the planning tools are abandoned; thus, when later on a new planning action is required, the construction of the planning tools must starts again from the scratch, with a loss of money, time and coherence. On the contrary, in the two level DSS the daily use of the DSS/M implies that the data base and the system model are regularly updated, then, since the DSS/P shares them with the DSS/M, the DSS/P is automatically updated.

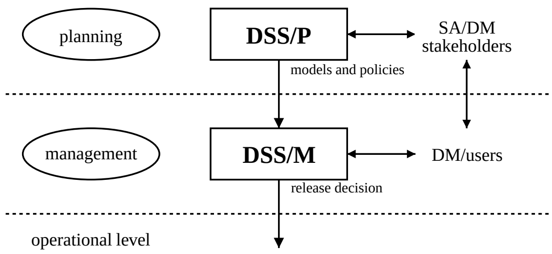

Figure 3: The two-level decisional process.

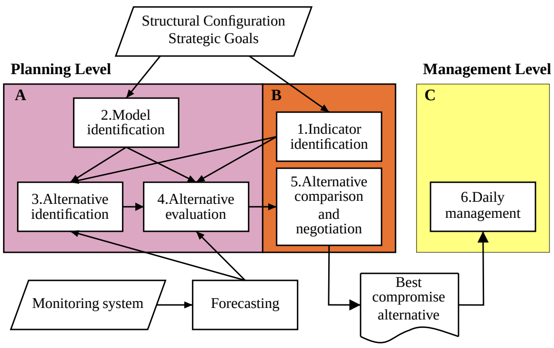

Figure 4: The phases of the two level decisional process.

4 SET-VALUED POLICIES

The definition of a management policy spawns from Control Theory, which was originally developed to control electro-mechanical systems. In such systems, the policy must allow for control in absence of human intervention, i.e. it must produce an *automatic* control. Examples of such policies are the autopilot of a jetliner or the speed controller of an engine. Since control must be automatic, at every time step the policy must return one and only one control decision: therefore the policy must be a point-valued function.

On the contrary, in the management of water systems the policy does not operate directly on dams and weirs, but proposes a control decision to the

DM. It will be up to the DM to accept the decision suggested. Note in fact that the optimality of a management policy does not refer to the real world complexity, but to a simplification of the real world, that is to a *scenario*. The scenario includes all the approximations that are beyond the used models and the selected objectives. For instance the structure of the downstream water distribution network is usually heavily simplified, the catchment model (which generates the reservoir inflows) is often modelled as a purely stochastic process. These simplifying assumptions are justified, from the SA viewpoint, since they are needed to reduce the optimal control problem to a solvable formulation, given the current mathematical and hardware tools, but they are perceived as deceiving by the DM. Given this fact, it would be more effective if the policy proposes not a single decision value u_t, but the set M_t (*safe control set*) of all the decisions that are equivalent (i.e., which guarantee in the long run the same performance of the policy) from the point of view of management objectives and for the models adopted to represent the real world (for details see Aufiero et al. [2001a] and Aufiero et al. [2001b]). The use of a *set-valued* policy would therefore allow the DM to choose at time t a decision among the optimal ones by taking into account new facts: e.g. secondary objectives (not included in the objective Z_i of problem 2a) that appear to him as particularly relevant at time t or the current situation (e.g. heavy rainfall on the catchment, power plant outages, etc.) that has not been considered in the scenario adopted in the policy design phase. In this way the level of confidence of the DM in the policy is widely improved. A straightforward consequence of the adoption of set-valued policies is that the controller where the policy is implemented (see phase 6 in Figure 4) must be a Decision Support System itself (that's the reason behind the acronym DSS/M), in order to enable the DM to evaluate and compare the effects of alternative choices of u_t in M_t.

5 SYSTEMS AND PERFORMANCES

We have seen how a planning alternative can be identified and how the design of set-valued management policies plays a central role in this process. We come now to the questions posed by the evaluation of each alternative.
The stakeholders having the same concerns and priorities are grouped in one *sector*, to which is associated an *index*. This one is a function of the alternative and expresses the stakeholders' satisfaction for it. The indexes are chosen in phase 1 and used in the successive phases to compare the alternatives. For a given sector the evaluation of the corresponding index is carried out in cooperation by the SA and the so-called *sector expert*. This is usually a technicians who is expected to support the stakeholders by translating their qualitative judgments into quantitative evaluations. Theoretically the sector expert could directly settle the index value for each alternative on the basis of its expertise (Figure 5-a). However this approach frequently leads to too subjective and hardly acceptable evaluations, that might further become imprecise when facing with a large number of alternatives. It would be then more appropriate to formalize a procedure to compute the index values automatically (Figure 5-b). This procedure should reproduce the expert skills and be identifiable through interviews.

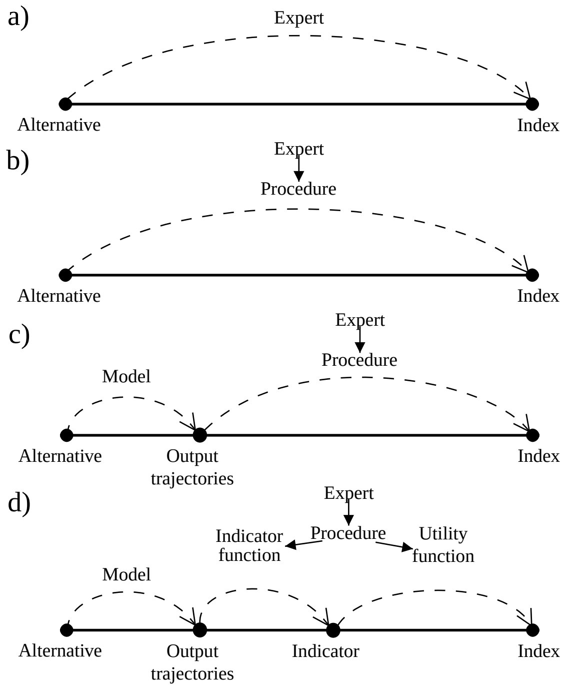

Figure 5: More and more articulated ways of structuring an index.

The dynamic nature of a water reservoir system implies that its evolution over a given time horizon may be completely described by the trajectories of the system outputs (i.e., reservoir water storages and release decisions). Hence an alternative modifies the trajectories of its outputs. The process of evaluating an index can thus be though of as a two step process (Figure 5-c):

1. the simulation of the controlled system over a given time horizon, by using the mathematical model of the system;

2. the computation of the index as a functional of the trajectories computed in the first step.

However the direct identification of an index through the simple observation of the system trajectories could again be a hard task for the sector expert. To further simplify the problem one or more intermediate indicators may be conveniently added between the trajectories and the index (Figure 5-d). These indicators must meet a precise condition: each one must be expressed by a separable function of the system variables, i.e. it must be the temporal aggregation of instantaneous indicators (the step costs $g_t^i(\cdot)$ in equation (2b)), such that the one at time t only depends on values of variables at the same time t. Notice that this condition implies that each step cost at time t cannot be dependent on the value of any step cost at previous times, i.e. the step costs can not be state variables of any system. This condition seems to be particularly restrictive, but it can always be met, by suitably enlarging the state of the system model (e.g. if the step cost depends upon its value at a previous time, it can simply be included among the state variables by adding a transition function that expresses its dynamics to the the model).

More in general the indicators should be easily obtainable given the trajectories and should make it easier for the expert to relate them to index. This latter step is usually covered by the well known MAVT through the definition of utility functions and therefore it will not be further discussed. We focus instead on model construction and indicator definition.
Both these steps require a wide interaction between the SA, the DM and the stakeholders, since they should "feel" the models adopted as well as the indicators selected. Only in this way the decisional process leads to evaluations that will be perceived as "trustable": *a direct involvement of the decision maker herself in the modelling process is the unique way to make credible models: these can in fact be built only by people who are familiar with both the problem and the institutional setting in which the problem is to be addressed* (Loucks et al. [1985]).

5.1 Models and indicators

The components of a water reservoir system are usually modelled by means of models, either simple "black-box" or complex physically based models, that can be represented by the following equation:

$$c_{t+1} = f_t\left(c_t, u_t, w_t, \varepsilon_{t+1}\right) \quad (3a)$$

$$y_t = h_t\left(c_t, u_t, w_t, \varepsilon_{t+1}\right) \quad (3b)$$

where c_t is the state variable, y_t is the output, w_t is the exogenous input to the component (that is generally the output of other components) and ε_{t+1} is a disturbance. All these models are markovian models. Once the state transition function $f_t(\cdot)$ and the output function $h_t(\cdot)$ have been properly structurally identified, they can be easily calibrated with the well known techniques of System Identification Theory (Ljung [1987]). Consider for instance the catchment: it can be described using a stochastic autoregressive models of order q, where c_t is the state of the catchment, y_t represents the outflow (i.e. the reservoir inflow) and ε_{t+1} is a disturbance that represents rainfall, temperature, etc.. Both $f_t(\cdot)$ and $h_t(\cdot)$ are linear functions, whose parameters values might be easily identified from historical inflow series.
However it may occur that the physical and socio-economical relations that underly some of the components are poorly known and/or it is comparatively expensive to obtain raw data to characterize them better. In these cases it might be difficult to identify the two functions $f_t(\cdot)$ and $h_t(\cdot)$. The SA is thus forced to formulate unrealistic simplifications, the majority of which are based on the assumption that the processes are well known and deterministic. But this assumption is often too reductive. Consider again the Verbano water system. A suitable way to low the water demands of the irrigation districts is to reduce the inefficiencies of the irrigation systems. A lower downstream water demand should in fact reduce the water storage required to reach a given level of supply satisfaction and, as a consequence, induces a reduction of flood risk on the lake shores. Thus the DM might wonder whether and what level of financial incentive will encourage the farmers to adopt more water-efficient irrigation systems. Intuitively what the DM expects is that the farmers' bent to modify their irrigation systems depends on the value of the incentive. But how can this bent be formalized in a model or in a indicator so that the effects of a given value of the incentive on the whole agriculture production can be assessed? Furthermore the uncertainty of the physical processes that influence water demand (e.g. net radiation, canopy cover) couples with a behavioural uncertainty (the proneness of farmers to change). How can such mixture of uncertainties be described?
A solution to tackle with these two different uncertainties is to adopt Bayesian Belief Networks (BBNs) (Jensen [1996], [2001]). BBNs are directed graphical models in which nodes represent random

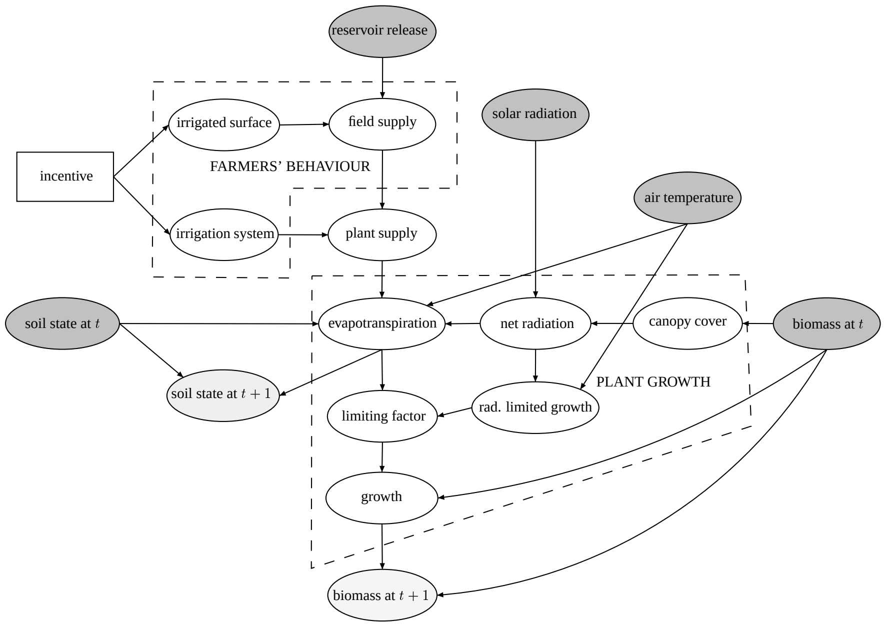

Figure 6: A BBN dynamic model of an irrigation district.

variables and the lack of arcs between two nodes represent the conditional independence of the two variables. Given two nodes A and B, one can regard an arc from A to B as indicating that A "causes" B. The model can be identified by specifying a Conditional Probability Table (CPT) at each node. A CPT lists the probability that the child node takes on each of its different values for each combination of values of its parents. BBNs can be effectively used to model those components of the system for which the knowledge is limited or unstructured, and the cause-effect relationships are not evident, as in the case of the above example. The insufficient prognoses on this type of processes would result in a weak description by simple deterministic or markovian models. On the other hand, for the components of system on which the knowledge is high and well structured (e.g. the hydrologic and hydraulic systems), the Bayesian approach would be cumbersome and redundant, while the stochastic description is perfectly suited (think for instance to the conservation of mass equation representing the reservoir dynamics).

To give an idea of how a BBN works consider the network of Figure 6, which describes an irrigation district, such the one of the Verbano example. Release, solar radiation, air temperature, soil state and biomass at time t (dark gray boxes) are the inputs of the model, while the financial incentive (squared box) is the planning variable; soil state and biomass at time $t+1$ are the model outputs (light gray boxes). Inputs and planning variables are called evidence variables, since given their value the (probabilities of the) values of all other the variables of the network may be inferred through evidence propagation. Since soil state and biomass appear both as input and output they are the state variables of the BBN, and the BBN can be seen as nothing but a particular way of writing equation 3. Notice that the BBN in Figure 6 contains two distinct sub-models: the first describes the farmers' behavior, the second the plant growth. The farmers, via the sector expert, are directly involved in identifying the first sub-model. They have to identify the items (parents nodes) that could in some way influence their choices (already done in Figure 6 and then express the probabilities of irrigating their fields and adopting a particular irrigation system conditioned to these items. The CPTs of the other sub-model may be filled either by interviews or by using a classical compartmental model (e.g. CROPSYS, Caldwell and Hansen [1993]). The process of filling in the CPTs is conceptually analogous to the calibration of a markovian model. It is now apparent that BBNs are nothing but a generalization of markovian models (Smyth [1998]). In conclusion BBNs appear to be the right instrument to represent the relationship between the water system variables and the indicators: when the relationship is of dynamical nature the equations (3) are used both (and then c_t is part of the water system state), while if the relationship is non dynamical only equation (3b) is active (since c_t is not existing). The first case happens when the farmers' indicator is the biomass at

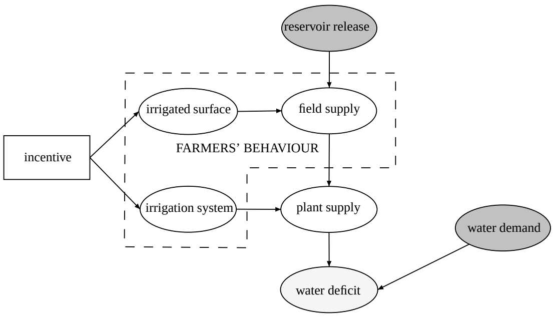

Figure 7: A BBN static model of an irrigation district.

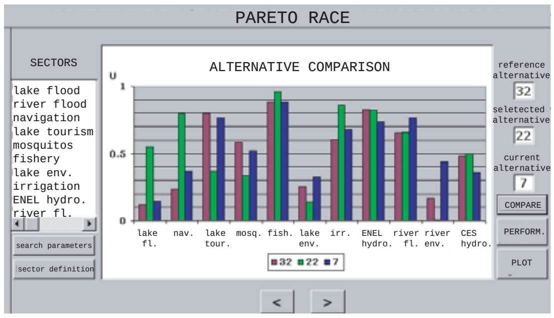

Figure 8: The alternative comparison.

crop time, the second when it is the supply deficit (see Figure 5.1).

6 Comparison and negotiation

Once all the alternatives generated have been evaluated, the SA can proceed to perform their comparison (phase 5). The most common approaches (e.g. Saaty [1980]) determine the *best compromise alternative* in two steps: first the stakeholders of each sector express their preferences among the sectors by means of weights, then the DM expresses his/her preferences among the stakeholders. In a way that depends on the adopted approach, these systems of preferences are merged into one, thus obtaining a vector of weights, one for each index. By means of this vector the set of alternatives may be ordered, ranking them from the most to the least desirable. To adopt one of these approaches it is mandatory that there exists one DM only, to whom the political power of specifying the social relevance of the different sectors is given, i.e. to whom the resolution of the conflict among the stakeholders is delegated .

Often this is not the case, as it is not in the case of the Verbano system: since the system is a transnational one, there are at least two DMs, the governments of Italy and of Switzerland. In this case the *best compromise alternative* is the result of a negotiation process between the two DMs. To supply the negotiation the set of alternatives has to be skimmed by identifying a set of *compromise alternatives*, each one preferred by a group of stakeholders and possibly refused by others. Obviously when there is only one compromise alternative, it has no opponents: therefore it is also the best alternative and the DMs have nothing to decide. On the contrary, it is the DMs' task to determine the *best compromise*. To accomplish this task they have to know, not only which are the alternatives of interest to the stakeholders, i.e. the set of the *compromise alternatives*, but also for each alternative who are the supporters and who the opponents.

This information can be produced by establishing a negotiation process among the stakeholders, that aims at identifying alternatives the consensus of which is as large as possible. Consensus does not imply complete agreement of the supporters, but means that each supporter feels reasonably comfortable and accepts the alternative as a feasible compromise with other supporters. A procedure to identify these alternatives can be derived from the so called Pareto Race (Korhonen [1988]; Korhonen and Wallenius [1988]). In its original version it is a procedure devised to help one single DM to search for the best compromise point on a Pareto boundary, without determining the whole boundary in advance. We do not have sufficient space and time to describe the modified Pareto Race procedure (see Soncini Sessa et al. [forthcoming]). We may only sketch the procedure by saying that the SA invites one stakeholder to indicate the alternative (s)he prefers among all the alternatives. Then the SA shows a diagram (Figure 6) of the utilities produced by the alternative in each sector and invites the stakeholders that feel unsatisfied to specify the reason. The set of alternatives is then explored to find out a new alternative that improves the utilities of the unsatisfied stakeholders, without lowering too much the utilities of the favorable ones. If such an alternative does exist the procedure is iteratively repeated, until it does not exist, then the current alternative is a compromise alternative. By repeating the procedure for each one of the stakeholders the set of the *compromise alternatives* is finally determined.

7 DSS ARCHITECTURE

We have already seen that the complex and recursive nature of the decisional process require a computer-based support system (DSS). In order to complete the picture, we will shortly describe the main features of its architecture, making reference to a prototype, named TwoLe (Soncini-Sessa et al. [1999]), that imbeds many (not yet all) of the ideas presented in this paper.

A traditional DSS gives access to data from an unstructured database; we think it is more appropriate that the database architecture is tailored to obtain independence between data, models and processing algorithms. For that reason the database of TwoLe has been partitioned in three different modules: the *domain base* that contains the structural knowledge regarding data and time series; the *model base* that contains the description of mathematical models, both descriptive (simulation and forecast models) and prescriptive (decisional models, i.e. multi-objective optimal control problems); the *experimental base* that stores the formulation of model identification and/or policy design problems as well as their results. In other words data are stored following a hierarchical approach and manipulated according to an object-oriented paradigm. Data in the domain and model bases are classified into basic and compound objects. Building a basic object domain, e.g. a catchment or a reservoir, is the first modelling step, where raw data are organized by hypothesizing a modelling structure and its purposes; then a set of basic objects can be grouped to constitute a compound object, as a water system or a distribution network. On the same object, either basic or compound, different models can be built: the purpose of the model base is in fact to promote the model substitution and interconnection. The DSS/P and DSS/M use a common domain base and model base to perform their tasks. Finally, the *experiment metaphor* has been adopted to represent the SA activity: an experiment starts by choosing the necessary ingredients (data and/or models); continues by formulating a model identification problem or a multi-objective optimal control problem or a simulation; and ends by solving the posed problem and storing the results. To compute the problem solution, a tool (either an identifier or an optimizer or a simulator) is applied, which can be picked up from a tool box. TwoLe provides a set of standard identification tools, a wide choice of policy design optimizers and a bunch of simulators. The latter includes deterministic, markovian and Monte Carlo simulators while the optimizers are based on different algorithms such as stochastic dynamic programming (Bertsekas [1995]), neuro-dynamic programming (Bertsekas and Tsitsiklis [1996]; De Rigo et al. [2001]) or Q-learning (Watkins and Dayan [1992]); Castelletti et al. [2001]). All these algorithms have been conceived to deal with set valued policies.

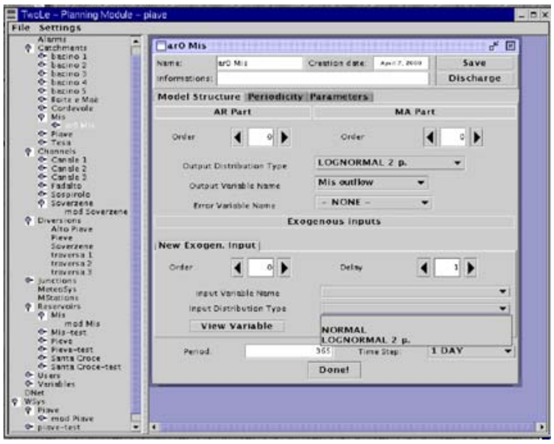

Figure 9: The TwoLe GUI: calibration of an ARMA.

The DSS control unit allows the communication between the two levels of the DSS and the domain, model and experiment bases. In the present version of TwoLe, by means of the DSS/P, the SA can edit data, design, calibrate and validate models, produce optimal distribution policies (network optimization) and optimal release policies (water system optimization), and evaluate the performance of alternatives by means of simulation. In other words it supports all the activities required to complete the phases 2-4 in box A of Figure 4. In the future it will also support phases 1 and 2 in box B. The DSS/M (box C) can presently deal with forecasting, by using real-time data from a telemetering network, and compute the daily release decision.
Finally Twole has a friendly user interface (GUI) to help the SA in data preparation and algorithm choice. The GUI is inspired by the *toolbox and folders* metaphor (see Figure 7): the SA can browse the folder structure as a normal file manager, and choose a tool to perform its tasks on the items stored in a folder. The folder structure is recursive: at top the level items are meta-domain objects; each one opens on real domain objects and, in turn, each domain contains its models and, for each model, the experiments that were made on or with it.

8 Conclusion

In this paper we have briefly review the main phases of the well known EIA procedure, pointing out some challenging and significant concerns posed by its application to planning and managing water reservoir systems. For each one of these issues we have proposed and analyzed some innovative solutions. In doing so we have stressed the key role played by a wider involvement of stakeholders and DMs at every stage of decisional process and suggested how this involvement could be technically pursued. Finally we have described some structural features of TwoLe, a two level DSS, which imbeds some of (not yet all) the ideas presented. TwoLe has been successfully applied to the planning of Verbano water system in Northern Italy (Betti et al. [2001]) and is currently adopted in the recently started EU project MERIT (Management Environmental Resources using Integrated Techniques) aimed at exploring the applicability of BBNs as an integrated management tool.

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