Model-based decision support for integrated management and control of coastal lagoons

Marco Casini, Chiara Mocenni, Simone Paoletti and Marco Pranzo

***Abstract*— This paper addresses some results obtained within the EU funded project DITTY as concerns the development of a decision support system for the management of Southern European lagoons. The first contribution is a general model-based decision support structure, whose development was motivated by the need for a common and flexible framework to ease the integration of the outputs of different project work-packages, as well as to deal with the diversity of socio-economic and environmental characteristics of the project case studies. The proposed structure helps integrate and manage in a clear and structured fashion the information provided by different kinds of mathematical and analytical models (e.g., biogeochemical, hydrodynamic, ecological, socio-economic models of a lagoon ecosystem). Data and information obtained from the models can be used to accomplish the decision task by application of multicriteria analysis approaches. Robustness of the decision is explicitly taken into account. As a second contribution, the effectiveness of the proposed decision support structure is shown through its real application to the management of clam farming in the Sacca di Goro lagoon (Italy).**

I. INTRODUCTION

Coastal lagoons are by nature complex systems characterized by large fluctuations in the physical and chemical parameters. This is primarily due to their location between land and open sea, which makes their equilibrium strongly influenced by the quality of inland waters flowing into them. Additional problems arise from cost erosion, subsidence and effects related to extreme meteorological events.

Over the last decades, coastal zones have also become an extremely valuable, but scarce, economic resource. The increase in value is mainly concerned with the enormous potential of coasts for residential, tourism, economic (mainly, shellfish/fish farming), and recreational development. On the other hand, concepts like sustainable use of the natural resources and sustainable coastal development have been often disregarded. Overcrowding, degradation of water quality, resource exhaustion, conflicting use of resources, multiple and uncoordinated ecosystem modifications (e.g., structural changes in lagoon topography, artificial increase of the number of sea connections, changes in bathymetry, etc.) undertaken with only limited sectorial objectives in mind, are some of the current issues associated with coastal areas, and contribute to the decrease of their economic potential. For these reasons, the prevention of further damage and the introduction of sustainable development concepts are being recognized worldwide as fundamental items in the regional planning and management processes of coastal zones.

In Europe, in particular, both the individual governments and the European Community invest considerable financial resources in research projects aimed at analysing and solving the problems related to coastal environments. Indeed, since these systems are subject to various kinds of anthropic pressures, which are often sources of conflicts among the different users, it is extremely difficult to balance the socio-economic interests with the environment safeguarding. In this respect, it is now widely recognized that integrated management, together with the development of interdisciplinary and multicriteria approaches, is the key to the sustainable, equitable and efficient development of lagoon resources. This means that decisions need to be taken in the light of not only environmental considerations, but also their economic, social, and political impacts. It requires also the active participation of stakeholders in the decision making process. The real problem is to find a practical way to achieve these aims.

A. Background and motivations

Mathematical models of the biological, physical and chemical processes are fundamental tools for analyzing disruptions in the lagoon ecosystem due to abnormal conditions. Some examples related to Mediterranean lagoons can be found in [1], [2], [3], [4], and references therein. However, the successful management of such complex systems requires the integration of the information provided by the mathematical models with other kinds of analyses. Socio-economic analysis assumes for instance great importance in coastal lagoons, where various kinds of anthropic pressures (aquaculture, fishery, tourism, etc.) are sources of conflicts among different users. Hence, to the aim of a successful integrated lagoon resource management, the following advances in research are considered as advisable [5]:

1) Modelling and decision making need to be undertaken in a more integrated way.
2) Methods for evaluating the economic and social impacts of new policies need to be developed and implemented.
3) Scenario-based approaches need to be developed to allow testing of potential policies and management changes before these are implemented.
4) Improved participation and awareness methods need to be developed, and their use fully understood.

This research has been supported by the EU funded project DITTY (Development of an Information Technology Tool for the Management of European Southern Lagoons under the Influence of River-Basin Runoff) in the Energy, Environment and Sustainable Development programme of the European Commission (EVK3-CT-2002-00084).

The authors are with the Dipartimento di Ingegneria dell'Informazione, Università di Siena, 53100 Siena, Italy, and also with the Centro per lo Studio dei Sistemi Complessi, Università di Siena, 53100 Siena, Italy (e-mail: casini@dii.unisi.it; mocenni@dii.unisi.it; paoletti@dii.unisi.it; pranzo@dii.unisi.it).

It is apparent that, through the integration of modelling approaches, management tools, and multicriteria analysis, a high development potential can be exploited to achieve successful results. To this aim, a suitable framework is represented by Decision Support Systems (DSS), i.e. information systems that assist decision making processes. Decision making means selecting between alternatives. The main function of a DSS is therefore to design, generate and present different alternatives, and provide tools for their comparative analysis, ranking and selection, given the decision-maker's criteria, objectives, and constraints.

In the last decade, decision support systems have been widely applied to the sustainable management of coastal basins and water resources. The interest on these tools is confirmed by the recent special issue [5], where several examples of integrated decision support tools for water resources management are presented. The reader is also referred to [6], [7], [8], [9], and references therein.

B. Paper contribution

The main contribution of this paper is a general model-based decision support structure that is applicable in multi-objective decision problems where several mathematical and analytical models of a (complex) system are available.

The proposed DSS structure was developed in the context of the EU funded project DITTY. One of the objectives of the project was the development of a prototypal decision support tool for the management of Southern European lagoons. Test sites of the project were the lagoons of Ria Formosa (Portugal), Mar Menor (Spain), Etang de Thau (France), Sacca di Goro (Italy), and Gera (Greece). The diversity of socio-economic and environmental characteristics of the case studies required a tool which was capable of a common approach to different decision cases, and responsive in a range of cultural, political and organizational contexts, but also flexible enough to adapt to the specific objectives and constraints of a particular decision problem. In addition, the core of each DSS implementation had to be represented by the mathematical and analytical models developed for each site in other phases of the project. The efforts were thus primarily directed toward the development of a general model-based DSS structure into which all site-specific decision problems could be cast.

The DSS structure includes a mechanism for generating the alternatives to be compared. The available models are used to simulate the system under each alternative, and to compute system performance indicators related to each decision criterion. Multicriteria analysis approaches are finally used to evaluate and rank the alternatives on the basis of both the values of the indicators and the interaction with the decision maker. Several multicriteria analysis tools [10], such as the Analytic Hierarchy Process [11], reference point [12] or ELECTRE [13] methods, can be applied to this aim. Robustness of the decision is taken into account in an effective way by explicitly distinguishing the sources of uncertainties, namely all the system inputs that are not controllable by the decision maker.

To the best of the authors' knowledge, the high-level block structure proposed in this paper for model-based decision support systems was not formalized before in the literature. Quite notably, several important decision support systems developed for specific applications, such as [8] and [14], fit the general structure proposed here. Hence, this structure represents a unitary framework for many decision support systems already designed, and provides an answer to "still open methodological questions about the development and *structure* of operational decision support systems with and for European decision makers in the field of water resource management" [15]. The significance of the proposed DSS structure is more thoroughly discussed in Section III-B.

Another contribution of this paper is the application of the proposed decision support structure to a real decision problem in the lagoon of Sacca di Goro (Northern Adriatic Sea, Italy). Here, the decision problem was concerned with the grant of new concessions for clam farming in the lagoon. The DSS response provided effective and useful support to the Administration of the Province of Ferrara, which decided at the end of 2005 to stop the grant of new concessions. Applications to the other DITTY project case studies are not reported in this paper due to space limitations. Another application of the proposed scheme is presented in [16], where particular emphasis is devoted to an optimization model for resource allocation in coastal lagoon areas characterized by shellfish farming and agriculture.

The paper is structured as follows. A short introduction to decision support systems is given in Section II. Section III describes and discusses in detail the proposed DSS structure, while Section IV illustrates its application to the Sacca di Goro lagoon. Conclusions are drawn in Section V.

II. Overview on decision support systems

A. Model-based decision support systems

Decision support systems cover a wide variety of systems, tools and technologies for informing and supporting decision makers. Based on the tool or component that provides the dominant functionality in a DSS, Power [17] proposes a taxonomy of decision support systems by distinguishing communication-based, data-based, document-based, knowledge-based, and *model-based* DSS.

Model-based decision support systems integrate different kinds of mathematical and analytical models for simulation and prediction of the system[1] behavior. Hence, model-based DSS exploit the full resolution and detail of simulation models, thus avoiding the pitfalls and limitations of the approximations often used for optimization. Key issues when designing a model-based DSS are the choice of appropriate models and software, and the definition of data formats. Very large databases are usually not needed for model-based decision support systems.

[1]We distinguish the *system*, i.e. the part of the real world (environment, people, activities, etc.) that is the object of the decision maker's interests and actions, and the *decision support system*, i.e. the tool for supporting the decisions.

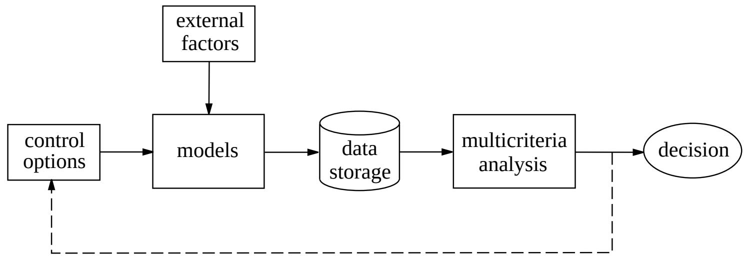

Fig. 1. High-level block scheme of the proposed model-based DSS architecture.

B. DSS terminology and logic

It is assumed that the decision problem is structured and presented in terms of:

- The *control options*, i.e. the alternative actions, strategies, and/or policies that can be undertaken to affect the system behavior.
- The *criteria* on which basis the system performance led by each control option is evaluated.
- The *objectives*, i.e. the type of optimization to be performed on each criterion.
- The *constraints*, establishing bounds for some/all the criteria in order to make the evaluated alternative acceptable or feasible.

The aim of the DSS is to support the choice of a control option that is both effective (i.e. meets the constraints) and efficient (i.e. optimizes the objectives). In this respect, the control option definition and design is of central importance. The control options are described by value assignments of the *controllable variables*.

Example. If local authorities are asked to grant new farming concessions for aquaculture, and have to decide the amount of such concessions, the allocated farming area is the controllable variable.

On the other hand, the *uncontrollable variables* describe external factors that are not subject to choice, but do affect the system performance. Their role in the DSS can be only viewed in terms of sensitivity and robustness of the final decision.

Example. Typical uncontrollable variables are the weather conditions and the water inflows for the biogeochemical models of a lagoon, and the prices and market data for the economic models.

The criteria are expressed by means of *indicators*, and are used to describe the system and evaluate its behavior and performance under alternative control options. The objectives correspond to indicators whose value has to be either maximized or minimized. The constraints impose a maximum and/or minimum value to the indicators. They may correspond to thresholds defined on the basis of regulations and/or experience, and allow to discard unacceptable alternatives. Additional variables that do not correspond to criteria, but the decision maker might want to constrain, are referred to as *internal variables*. Note that also the controllable and uncontrollable variables could be bounded in order to reflect both physical and practical constraints.

With the above definitions, the basic DSS logic is simple. A set of alternative control options for the system are generated by changing the values of the controllable variables. Each control option leads to a corresponding system performance, which is expressed by indicators. Performances are analyzed, evaluated and compared by means of suitable multicriteria analysis tools to arrive at the final preference ranking of the alternatives, and the eventual choice of a preferred alternative as the solution of the decision process.

III. The Proposed DSS Architecture

Once the decision problem has been identified, and structured in terms of control actions, criteria, objectives, and constraints, the main elements of a decision include the design of promising, feasible alternatives and the subsequent selection of a (possibly optimal) solution from a set of alternatives thus generated or identified.

Following the basic DSS logic described in Section II-B, the scheme of the proposed model-based DSS architecture is shown in Fig. 1, where the models play a key role between the control option generation and the performance evaluation and comparison (multicriteria analysis). The different component blocks of the DSS architecture will be described in detail in the following. Here, it is stressed that the proposed DSS architecture may answer both "what-if" and "how-to" questions, since simulation models perform scenario analysis, while optimization/satisfaction is addressed in the multicriteria analysis section. In addition, a feedback mechanism makes it possible to adapt the set of evaluated alternatives in order to meet the given objectives.

A. Blocks description

1) Control options: The block "Control options" provides the alternative (pre-existing or generated on demand) control options by assigning different values to the controllable variables. A discrete approach is assumed, where a finite (possibly very large) set of alternatives is considered. Assuming that p controllable variables are considered, and n different alternatives are generated, the p-dimensional vector V_i contains the values assigned to the controllable variables in the ith alternative, $i = 1, ..., n$.

The generation mechanism is not specified, since it may depend on the application. Note that the discrete approach does not guarantee optimality, so that the smaller the set to choose from, the less likely it will contain a good (in some sense optimal) solution. On the other hand, for highly complex systems it can be the only possible approach, which implies that one should always attempt to generate the largest possible number of alternatives.

The generation mechanism can effectively exploit the *feedback* from the multicriteria analysis stage in order to extend or adapt the set of possible solutions in response to the user's preferences. Indeed, concrete solutions which have been formulated and analysed typically bring a deeper insight and understanding of what the problem actually is, and how it could be better solved. In addition, in some cases the alternative options are not readily available, and have to be discovered.

2) External factors: This block provides values for the uncontrollable variables describing the external factors that cannot be controlled/manipulated by the decision maker, but are required for the accurate system simulation, and affect its performance.

Uncontrollable variables represent the uncertainty affecting the decision process. Inadequate values assigned to them could invalidate the results of the study. Hence, their role in the DSS can be viewed in terms of sensitivity and robustness of the final decision (see the subsequent Remark 3.1).

3) Models: This block represents a suitable interconnection of the models used to describe the system behavior. The use of models is twofold:

- To make simulations and predictions of, e.g., the physical, chemical and biological, as well as the economic and social variables of the system.
- To compute the performance indicators for a quantitative assessment of the evaluated control option.

When the ith control option is considered, $i = 1, ..., n$, the block "Models" receives as inputs both the controllable variables characterizing that particular control option, and the uncontrollable variables. The block output is an m-dimensional vector I_i (where m is the number of criteria) containing the values of the system performance indicators under the ith control option. Possible constraints imposed on the indicators, as well as on the internal variables, are checked during the simulation. If one or more constraints are violated, the considered alternative is discarded as infeasible.

The internal structure of the block "Models" primarily depends on the type of available models, and hence is case specific. Fig. 2 shows the block components and their interconnections in the application developed for the Sacca di Goro lagoon.

Remark 3.1: For a given control option, the values of the performance indicators are clearly affected by the uncontrollable variables. Hence, in order to perform a fair evaluation of different alternatives, the system performance must be compared under the same external conditions. In addition, in order to make the DSS more robust with respect to varying external conditions, robustness analysis can be performed through both statistical and scenario analysis techniques. For instance, it is strongly recommended to evaluate and compare the alternative options for several value assignments of the uncontrollable variables, and then to consider an average ranking, as described in Section IV-D.2.

4) Data storage: For fixed external conditions, the values of the performance indicators corresponding to the n evaluated control options are stored in the $n \times m$ matrix

$$I = [\, I_1 \ \ldots \ I_n \,]^\top. \tag{1}$$

5) Multicriteria analysis: If only the jth criterion is considered ($j = 1, ..., m$), the best control option can be simply selected by taking the optimum over the jth column of (1). However, when all the m criteria are considered, it happens very likely that the optimum over each column is not achieved by the same control option. In this case the selection of the best alternative (namely, the one which achieves the most suitable trade-off) is neither direct nor intuitive. This justifies the need for multicriteria analysis tools.

Numerous algorithms to solve multiple-criteria decision problems have been developed during recent decades (see, e.g., [10] and references therein). The methods differ in the type of information they request, the methodology used, the sensitivity tools they offer, and the mathematical properties they verify. Indeed, practical applications of the multicriteria approach are hindered by the ambiguity of choosing one particular method among all those available. Each method may potentially lead to different rankings, and the choice of a methodology is subjective and dependent on the decision maker's predisposition.

In the Sacca di Goro application illustrated in Section IV, the adopted multicriteria analysis tool is the Analytic Hierarchy Process [11], but the use of different tools, such as reference point (Wierzbicki, 1998) or ELECTRE (Roy, 1991) methods, is also possible in the proposed structure.

B. Discussion

The DSS structure described in Section III-A represents a valuable contribution in view of the items in Section I-A:

- The clear high-level block structure facilitates model-based DSS design by presenting in a very simple, intuitive, and clear conceptual scheme the logic flow from the definition of the alternatives to their comparative evaluation by means of multicriteria analysis. Hence, it fulfills item 1 of Section I-A in two ways:
  - It calls the DSS development to drive the entire study. In many DSS projects the DSS is considered at the very end of the project, with the only aim of adding value and justification to whatever analysis went before. More correctly, the prior definition of the DSS structure focuses complementary steps such as data compilation, development of models and indicators, scenario analysis, etc., to the requirements of the DSS, to be sure that the information finally available is complete, meaningful, and relevant to the decision problem at hand.
  - It enables a clear definition of communication protocols, data flows, interchange formats, inputs and outputs needed by and from the models, etc.

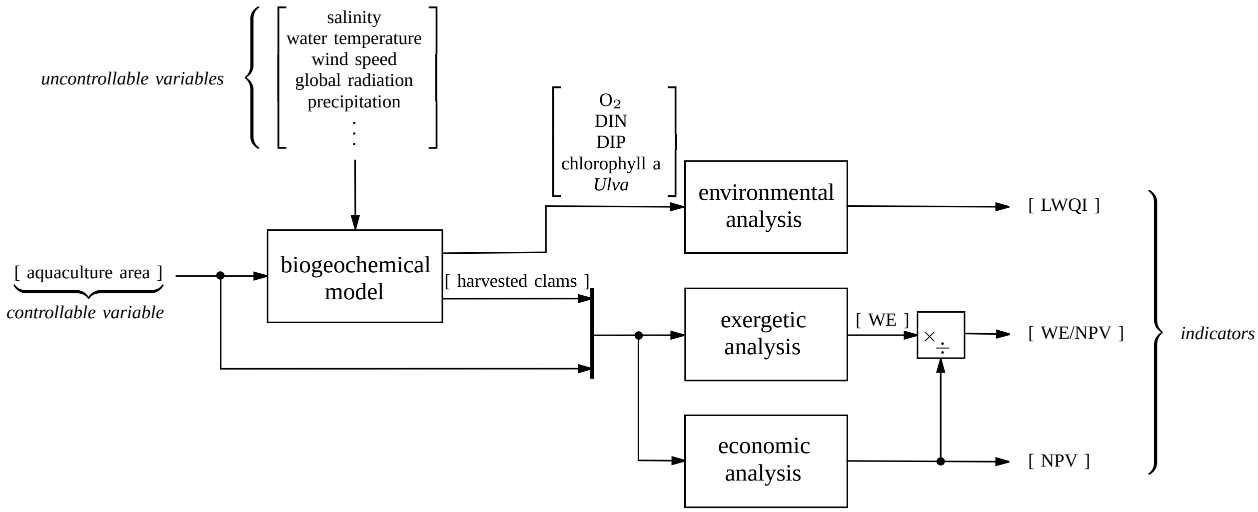

Fig. 2. Internal structure of the block "Models" in the application of the proposed DSS scheme to the Sacca di Goro lagoon case study.

- The proposed DSS structure emphasizes the role of mathematical and analytical models for simulation of the alternatives and performance assessing. In this respect, it allows for the integration of the methods developed in view of item 2 of Section I-A.
- It allows for the implementation of "what-if" approaches, in view of item 3 of Section I-A. "How-to" questions can be also addressed by virtue of multicriteria analysis, and a feedback mechanism which makes it possible to adapt the set of evaluated alternatives in order to meet the given objectives.
- The block structure, which is the result of an effort of simplification and abstraction, achieves item 4 of Section I-A by making the decision process more transparent to stakeholders, but also to model developers, who might not have the know-how in the field of decision support and optimization. In particular, the concept of robustness of the decision is clearly made accessible by explicitly distinguishing the sources of uncertainties.

Finally, it is stressed that the modularity of the proposed DSS structure both simplifies the debugging, and allows for a continuous development of the DSS. Indeed, the structure is prepared to take advantage of the availability of new or more accurate models, which can be easily plugged into it. The more detailed the models, the more reliable the DSS responses, without any limitation imposed by the structure.

IV. Application: The Sacca di Goro Lagoon

In this section the proposed DSS structure is applied to the management of clam farming in the Lagoon of Sacca di Goro (Northern Adriatic Sea, Italy). Sacca di Goro is a coastal lagoon with a surface area of 26 km^2 situated at the south edge of the delta of the Po River. Here, local authorities are asked to grant new farming concessions for aquaculture, and have to decide the amount of such concessions. However, since shellfish farming activities are responsible for important ecosystem disruptions, it is expected that increasing the farming area will very likely result into a worsening of the ecosystem health. Hence, the aim of the DSS is to help the local authorities in finding a suitable trade-off between the socio-economic interests and the environment preservation.

A. Decision problem definition

The decision problem of interest is summarized in Table I following the terminology introduced in Section II-B. The continuous involvement of the end-users in the definition of the criteria, objectives and constraints was fundamental to elicit their expectations.

The only possible action available to end-users concerns the amount of hectares of new concessions granted to clam farmers. Constraints on the minimum and maximum allocable aquaculture area are set: 1300 ha corresponds to the current allocated area, while 1450 ha is the maximum extension the administrators estimate as feasible. Three indicators (described in Section IV-B) are considered for assessing the performance of the evaluated control options:

- The Net Present Value (NPV) of aquaculture cash flows takes into account the pure economic aspect of the problem. End-users aim at maximizing the aquaculture revenue to boost the economic development of the area.

TABLE I

Decision problem definition for the Sacca di Goro Lagoon

Control actions	*Controllable variables*	*Constraints*
Grant new farming concessions	Aquaculture area [ha]	min: 1300 max: 1450

Criteria	*Indicators*	*Objectives*	*Constraints*
Aquaculture revenue	NPV [MEuro]	maximize	–
Environmental vs economic balance	WE/NPV [MJ/Euro]	minimize	–
Water quality	LWQI [%]	maximize	–

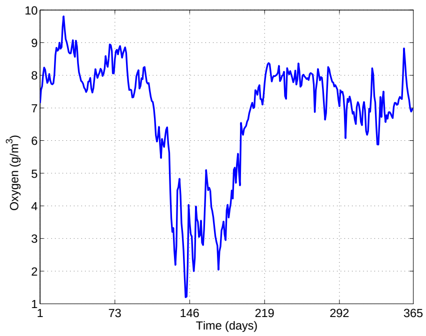

Fig. 3. Oxygen dynamics simulated by the biogeochemical model of the Sacca di Goro under "dry" external conditions and 1350 ha aquaculture area. It can be seen (not reported in this plot) that anoxic crises correspond to peaks in the production of *Ulva*.

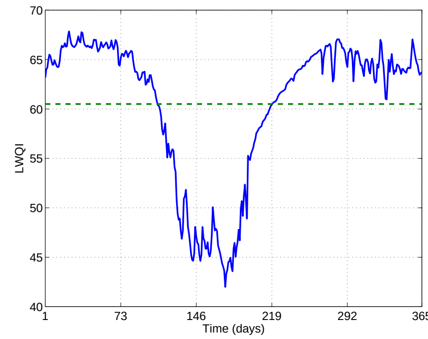

Fig. 4. Plot of the LWQI. The oxygen (see Fig. 3), DIN, DIP, and chlorophyll-a concentrations, as well as the macroalgae coverage, are provided by the biogeochemical model of the Sacca di Goro. The dashed line represents the average LWQI value.

- The Lagoon Water Quality Index (LWQI) expresses a pure environmental criterion related to water quality. Local administrators aim at preserving water quality, and hence at maximizing this indicator, in order to ensure a sustainable development.
- The ratio of the Wasted Exergy (WE) to the NPV for the aquaculture economic sector (denoted by WE/NPV) expresses a mixed environmental and economic criterion. Minimizing this indicator corresponds to a more efficient use of the lagoon ecosystem.

B. Models

The internal structure of the block "Models" in the proposed application is shown in Fig. 2. A biogeochemical model represents the core of the structure, since it provides simulated values of the main biological, physical and chemical parameters of the lagoon, as well as predictions of the clam production. These values are used to perform various kinds of analyses (namely, environmental, exergetic, and economic analyses), and to compute the set of indicators characterizing the performance of the simulated alternative.

The component blocks in Fig. 2 are described with more detail hereafter. It is stressed that not all the uncontrollable inputs are shown in Fig. 2, both for clarity of the scheme and since, in the first approximation, some of them can be considered certain (e.g., unit prices and costs for the economic analysis).

1) Biogeochemical model: The 0D biogeochemical model of the Sacca di Goro lagoon proposed in [3] is used for dynamic simulation of the main biological, physical and chemical parameters of the ecosystem. The model considers the nutrient cycles, and the phytoplankton, zooplankton and macro-algae (*Ulva*) dynamics. The oxygen dynamics and the shellfish farming are also modelled. Nutrients from the watershed, wet and dry deposition, temperature, light intensity, wind speed, etc., are considered as uncontrollable inputs, while the aquaculture area is the controllable input. The model outputs that are used for performance analysis, are shown in Fig. 2.

The time resolution of the model is daily. Fig. 3 shows the plot of the oxygen dynamics over one-year simulation under forcing conditions measured in a dry year. Anoxic crises (deficiency of oxygen) are particularly evident.

2) Economic analysis: The NPV represents the aquaculture revenue, and is computed as the difference between benefits (the income from the sale of clams) and costs (e.g., salaries, costs for dredging and harvesting, etc.). All cash flows are discounted back to their present value. In the first approximation, the benefits are proportional to the harvested clams, while the costs are proportional to both the aquaculture area and the harvested clams.

3) Environmental analysis: The LWQI [18] is based on the WQI of the National Sanitation Foundation (NSF), and on the standards of the Organisation for Economic Cooperation and Development (OECD). It takes into account six environmental indicators, namely dissolved oxygen, dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), chlorophyll-a, macroalgae coverage, and phanerogams coverage. It is computed according to the formula

$$\mathrm{LWQI} = \sum_{j=1}^{6} w_j \, f_j(v_j) \tag{2}$$

where w_j are nonnegative weights which sum up to 1, and $f_j(\cdot)$ is a suitable value function transforming the indicator v_j into a quality index between 0 and 100.

The plot of the LWQI corresponding to the above mentioned one-year simulation is shown in Fig. 4. By comparing it with Fig. 3, one may note that the index is worse when the system shows bad health status, like during anoxic crises. It is worthwhile to stress that, to perform multicriteria analysis, the average LWQI value over time is considered (see again Fig. 4). Since the deterioration of water quality in recent years has determined the death of phanerogams in the lagoon, phanerogams coverage is neglected in LWQI computations.

4) Exergetic analysis: The exergetic analysis is aimed at evaluating the modifications to the lagoon ecosystem induced by anthropic exploitation. The thermodynamic definition of exergy is the amount of work that a system can perform by being brought into equilibrium with its environment. For a given economic sector, the Wasted Exergy (WE) is a measure

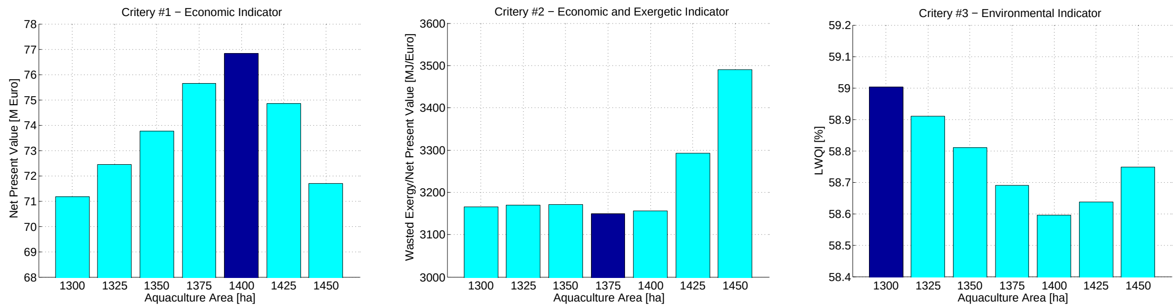

Fig. 5. Plots of the performance indicators (NPV, WE/NPV, and LWQI,) versus the aquaculture area for fixed weather conditions. The dark bar in each plot denotes the best option according to the corresponding criterion.

of the consumption of renewable and non-renewable exergy related to the production of that economic sector, where production is intended as the aggregate of marketable products (e.g., clams and mussels for aquaculture). Operatively, it is defined as the difference between the input and the output exergy of the production process.

The ratio WE/NPV for the aquaculture economic sector is used as a mixed environmental and economic criterion [19]. It can be interpreted as the amount of ecosystem "health" lost per unit of revenue. Hence, the smaller is the ratio WE/NPV, the more sustainable are the production activities for the environment.

C. Multicriteria analysis

In this application the adopted multicriteria analysis tool is the Analytic Hierarchy Process (AHP) [11]. The AHP may aid the decision maker to set priorities and make the best decision by reducing complex decisions to a series of pairwise comparisons, and then synthesizing the results. In addition, the AHP incorporates a useful technique for checking the consistency of the decision maker's evaluations, thus reducing the bias in the decision making process.

The AHP considers a set of criteria, and a set of alternative options among which the best decision is to be made. A weight is generated for each criterion based on the decision maker's pairwise comparisons of the criteria. The higher the weight, the more important the corresponding criterion. Next, for a fixed criterion, relative scores are attributed to the alternatives with the same pairwise comparison mechanism. The higher the score, the better the performance with respect to the considered criterion. Finally, the AHP combines the weights and the scores, thus determining a global score for each option, and a consequent ranking. The global score for a given option is a weighted sum of the scores it obtained with respect to the single criteria.

The pairwise comparison matrix A of the criteria is an $m \times m$ matrix where each entry a_{jk} represents the importance of the jth criterion relative to the kth criterion. If $a_{jk} > 1$, then the jth criterion is more important than the kth criterion, while if $a_{jk} < 1$, then the jth criterion is less important than the kth criterion. If two criteria have the same importance, then a_{jk} is 1. The entries a_{jk} and a_{kj} satisfy the constraint

$$a_{jk} a_{kj} = 1. \tag{3}$$

Obviously, $a_{jj} = 1$ for all j. The relative importance of two criteria is measured according to a numerical scale from 1 to 9, so that the larger a_{jk}, the more important is the jth criterion compared to the kth criterion.

D. Results

This section presents two different types of results that help show different aspects of the decision process. For a clear visualization of the results, only $n = 7$ control options, obtained by varying the aquaculture area from 1300 to 1450 ha with steps of 25 ha, are evaluated and compared. Clearly, more detailed simulations can be performed, if needed. Indeed, a possible use of the DSS is first to consider a rough set of options ranging from a minimum aquaculture area (corresponding to the policy of maintaining the current situation) to a maximum area (the maximum allocable aquaculture area) and, in a second phase, to refine the search in the most promising zone.

In particular, the presented results are obtained by varying the criteria weights in order to show the ability of the DSS to model the preferences and the objectives of end-users. Moreover, robustness issues are illustrated by showing results related to the variations of the external factors. The aim is to select a control option that is robust with respect to varying climate conditions.

1) Varying the criteria weights: The system is simulated over a time horizon of three years with seven different values of the aquaculture area. Normal weather conditions are assumed in all simulations. The plots of the performance indicators (NPV, WE/NPV, and LWQI) are shown in Fig. 5, where the system nonlinear behavior is evident. Different weights for the criteria are obtained by the AHP based on the pairwise comparison matrices

$$A_1 = \begin{bmatrix} 1 & \frac{1}{3} & \frac{1}{5} \\ 3 & 1 & \frac{1}{3} \\ 5 & 3 & 1 \end{bmatrix}, \quad A_2 = \begin{bmatrix} 1 & 3 & 5 \\ \frac{1}{3} & 1 & 3 \\ \frac{1}{5} & \frac{1}{3} & 1 \end{bmatrix}. \tag{4}$$

Note that A_1 privileges the environmental criterion (expressed by the third indicator, LWQI), while A_2 privileges the economic criterion (expressed by the first indicator, NPV). The corresponding AHP scores are shown in Fig. 6. By comparing Fig. 5 and Fig. 6, it is evident that the AHP is actually able to reflect the decision maker's preferences.

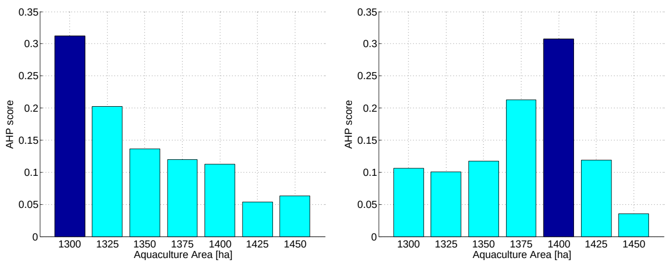

Fig. 6. AHP scores obtained with different criteria weights. Left: Privileging the environmental criterion. Right: Privileging the economic criterion. The dark bar in each plot denotes the decision supported by the AHP.

Clearly, more complex situations can be devised by setting appropriately the decision maker's preferences.

2) Varying the external factors: The alternative control options corresponding to seven different values of the aquaculture area are again considered. The system performance led by each alternative over a time horizon of two years is evaluated under nine external conditions corresponding to all combinations of dry (D), normal (N), and wet (W) years. The aim is to point out the best control option when there is uncertainty in the external factors that may influence the decision.

The criteria pairwise comparison matrix A_2 is used in the AHP. For each external condition, the scores associated by the AHP to the different alternatives are reported in Table II. In each row, the highest score is highlighted in bold. In order to select a reliable option, the mean score for each alternative is computed by averaging the entries on the corresponding column. By comparing the last row of Table II with Fig. 6 (right), it can be seen that, when robustness issues are taken into account by considering the variability of the external factors, the DSS solution settles at low values of the aquaculture area, even though the economic criterion is privileged. This suggests that the expected economic growth related to increasing the aquaculture area (and thus the clam production) does not compensate the environmental losses.

V. Conclusions

In this paper, a general structure for model-based decision support systems has been presented. It allows to integrate mathematical models for system simulation, and the computation of indicators for performance evaluation. Several multicriteria analysis tools can be incorporated to support decisions when multiple and conflicting criteria are present. Robustness of the decision is explicitly taken into account. The application of the proposed DSS structure to the management of aquaculture in the lagoon of Sacca di Goro (Italy) has been reported. Current work is focusing on the integration of GIS databases in the DSS structure, as well as its application to different decision problems.

TABLE II

AHP scores under different external conditions

	1300	1325	1350	1375	1400	1425	1450
D-D	0.099	0.149	0.255	**0.286**	0.042	0.069	0.100
D-N	0.119	0.108	0.163	0.173	**0.310**	0.096	0.031
D-W	0.311	**0.337**	0.116	0.066	0.046	0.053	0.072
N-D	0.176	0.269	**0.294**	0.102	0.074	0.049	0.037
N-N	0.124	0.096	0.099	0.150	0.186	**0.287**	0.058
N-W	0.106	0.108	0.170	0.119	**0.214**	0.082	0.201
W-D	**0.286**	0.134	0.177	0.283	0.032	0.036	0.052
W-N	0.194	0.242	**0.351**	0.037	0.039	0.052	0.086
W-W	0.291	**0.369**	0.119	0.038	0.039	0.061	0.083
mean	0.190	**0.201**	0.194	0.139	0.109	0.087	0.080

References

[1] G. Arhonditsis, G. Tsirtsis, M. O. Angelidis, and M. Karydis, "Quantiification of the effects of nonpoint nutrient sources to coastal marine eutrophication: applications to a semi-enclosed gulf in the Mediterranean Sea," *Ecol. Model.*, vol. 129, no. 2-3, pp. 209–227, 2000.

[2] A. Chapelle, A. Ménesguen, J.-M. Deslous-Paoli, P. Souchu, N. Mazouni, A. Vaquer, and B. Millet, "Modelling nitrogen, primary production and oxygen in a Mediterranean lagoon. Impact of oysters farming and inputs from the watershed," *Ecol. Model.*, vol. 127, no. 2–3, pp. 161–181, 2000.

[3] J. M. Zaldìvar, E. Cattaneo, M. Plus, C. N. Murray, G. Giordani, and P. Viaroli, "Long-term simulation of main biogeochemical events in a coastal lagoon: Sacca di Goro (Northern Adriatic Coast, Italy)," *Continent. Shelf Res.*, vol. 23, no. 17–19, pp. 1847–1875, 2003.

[4] A. Garulli, C. Mocenni, A. Tesi, and A. Vicino, "Integrating identification and qualitative analysis for the dynamic model of a lagoon," *Int. J. Bifurcat. Chaos*, vol. 13, no. 2, pp. 357–374, 2003.

[5] R. A. Letcher and C. Giupponi, Eds., "Special issue on policies and tools for sustainable water management in the European Union," *Environ. Model. Software*, vol. 20, no. 2, pp. 93–271, 2005.

[6] R. Pastres, C. Solidoro, G. Cossarini, D. Melaku Canu, and C. Dejak, "Managing the rearing of *Tapes philippinarum* in the lagoon of Venice: A decision support system," *Ecol. Model.*, vol. 138, no. 1–3, pp. 231–245, 2001.

[7] S. Pallottino, G. M. Sechi, and P. Zuddas, "A DSS for water resources management under uncertainty," in *Integrated Assessment and Decision Support*, A. E. Rizzoli and A. J. Jakeman, Eds., vol. 2. iEMSs, 2002, pp. 96–101.

[8] A. Carvalho, "Simulation tools to evaluate sustainable development in coastal areas," in *Proc. Littoral 2002, The Changing Coast*. Porto, Portugal: EUROCOAST/EUCC, 2002.

[9] K. Fedra, "Water resources simulation and optimization: A web based approach," in *Proc. 5th Int. Conf. Model., Simulat. and Optim.*, Oranjestad, Aruba, 2005.

[10] J. Figueira, S. Greco, and M. Ehrgott, Eds., *Multiple Criteria Decision Analysis: State of the Art Surveys*, ser. Int. Series Op. Res. & Manage. Sc. Boston: Springer-Verlag, 2005, vol. 78.

[11] T. L. Saaty, *The Analytic Hierarchy Process*. New York: McGraw-Hill, 1980.

[12] A. P. Wierzbicki, "Reference point methods in vector optimization and decision support," Int. Inst. for Applied Systems Analysis, Laxenburg, Austria, Tech. Rep. IR-98-017, April 1998.

[13] B. Roy, "The outranking approach and the foundations of ELECTRE methods," *Theor. Decis.*, vol. 31, no. 1, pp. 49–73, 1991.

[14] J. Mysiak, C. Giupponi, and P. Rosato, "Towards the development of a decision support system for water resource management," *Environ. Model. Software*, vol. 20, no. 2, pp. 203–214, 2005.

[15] J. Mysiak, C. Giupponi, and A. Fassio, "Decision support for water resource management: An application example of the MULINO DSS," in *Integrated Assessment and Decision Support*, A. E. Rizzoli and A. J. Jakeman, Eds., vol. 1. iEMSs, 2002, pp. 138–143.

[16] M. Casini, C. Mocenni, S. Paoletti, and A. Vicino, "A decision support system for the management of coastal lagoons," in *Proc. 16th IFAC World Congress*, Prague, Czech Republic, 2005.

[17] D. J. Power, *Decision Support Systems: Concepts and Resources for Managers*. Westport, CT: Quorum Books, 2002.

[18] P. Viaroli, M. Austoni, M. Bartoli, G. Giordani, D. Nizzoli, and J. M. Zaldivar, "Indicators of ecosystem functions, alterations and quality in coastal lagoons," in *Proc. 2nd Int. Conf. Coastal Lagoons*, Klaipeda, Lithuania, 2005.

[19] D. Verdesca, M. Federici, L. Torsello, and R. Basosi, "Exergy-economic accounting for sea-coastal systems: A novel approach," *Ecol. Model.*, vol. 193, no. 1–2, pp. 132–139, 2006.