Decision support system development for integrated management of European coastal lagoons

Marco Casini, Chiara Mocenni, Simone Paoletti, Marco Pranzo

Dipartimento di Ingegneria dell'Informazione e Scienze Matematiche
Università degli Studi di Siena
Via Roma 56, 53100 Siena, Italy
Email: {casini, mocenni, paoletti, pranzo}@dii.unisi.it

Abstract

In this paper, a general framework for the development of Decision Support Systems (DSSs) for the management of coastal lagoons is presented. The proposed DSS structure integrates the information provided by several models accounting for different characteristics of lagoon ecosystems, including biogeochemical, hydrodynamic, ecological and socio-economic aspects. Outputs and indicators provided by the models are used to accomplish the decision task by the application of multicriteria analysis. Model uncertainty and robustness with respect to uncontrollable factors are addressed. Application of the proposed DSS structure to five lagoons located in the Mediterranean area is discussed, with special focus on the management of clam farming in the Sacca di Goro lagoon (Italy). Thanks to its flexibility, the proposed DSS structure is also applicable in decision problems arising in different fields.

Keywords: Model-based decision support systems, analytic hierarchy process, coastal lagoon management

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1. Introduction

Coastal lagoons are by nature complex and fragile systems characterized by large fluctuations in their 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. Over the last decades, they have also become an extremely valuable economic resource. The increase in value is mainly concerned with the enormous potential of these sites for residential, tourism and economic (shellfish/fish farming) development. ~~On the other hand~~ However, concepts like sustainable use of natural resources and sustainable coastal development are 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. Hence, it is apparent that decisions need to be made in an integrated way by taking into account economic, environmental, social, and political aspects.

Moreover, the European Community has adopted the concept of *Integrated Water Resource Management* (IWRM) as an integral part of the Water Framework Directive (European Commission, 2000). IWRM recognizes that the impact of management decisions is not restricted to the water resource itself, but inevitably affects a range of stakeholders with interests in the area. To make a balanced and fair judgment, a planner must be able to evaluate the effects of a decision based on a wide range of factors, and to take into account all the types of benefits and drawbacks. In this respect, the development of interdisciplinary and multicriteria approaches is one possible key to the sustainable management of lagoon resources, as stated by the following guidelines (Letcher and Giupponi, 2005):

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.
3. Scenario-based approaches need to be accounted for in order to allow testing of potential policies and management changes before these are implemented.
4. ~~Improved participation and awareness methods~~ Methods need to be developed ~~, and their use fully understood.~~ for improving participation and awareness of all the actors involved.

~~Motivated by the third guideline above, in this paper we consider *model-based* DSSs, i.e., a special class of DSSs characterized by the integration of different kinds of mathematical and analytical models (Power, 2002; Casini~~

~~et al., 2007).~~ Decision Support Systems (DSSs) are computer-based information systems designed to support complex decision-making activities. Among various types of DSSs, *model-based* DSSs are characterized by the integration of different kinds of mathematical and analytical models (Power, 2002; Casini et al., 2007), and therefore may be suitable to meet the requirements of the third guideline above. For a given system under consideration (e.g., a coastal lagoon), models used in a DSS are required to describe the cause-effect relation between the actions available to decision makers and the system response to them. Therefore, models make it possible to simulate and predict the system behavior, thus providing useful information to the decision making process. Availability of accurate models is extremely important when dealing with lagoon ecosystems, since decision makers needs to consider the complex nonlinear behaviors of biological, physical, chemical and socio-economic processes. Some examples of models developed for Mediterranean lagoons can be found in Arhonditsis et al. (2000); Chapelle et al. (2000); Garulli et al. (2003); Zaldìvar et al. (2003), and references therein.

The main contribution of this paper is a simple, general framework for the development of model-based DSSs for water resource management. The proposed DSS framework was developed in the context of the EU funded project DITTY (Development of an information technology tool for the management of southern European lagoons under the influence of river-basin runoff). In this project, all DSS applications were related to the management of Southern European lagoons. The diversity of socio-economic and environmental characteristics of the considered case studies motivated the development of a general model-based DSS structure into which all site-specific decision problems could be cast. For this reason, the proposed framework is not limited to coastal lagoon applications, rather it is applicable in a variety of ~~contexts~~ water resource management problems, since it represents an open, modular and simple structure which may guide even inexpert users in developing their own DSS and gaining confidence in it. Another contribution of the paper is the model-based DSS designed according to the proposed framework for a real decision problem faced by local administrators in the Sacca di Goro lagoon (Italy).

The paper is structured as follows. Section 2 reviews the literature on water management DSSs. Section 3 describes the proposed model-based DSS framework. The application to the Sacca di Goro lagoon is detailed in Section 4, while the description of other case studies of the DITTY project and a discussion on strengths and weaknesses of the proposed DSS framework is reported in Section 5. Finally, conclusions are drawn in Section 6.

2. Background and literature review

A large body of literature in the field of ~~managing~~ complex environmental systems management deals with stating the correct methodologies for the development of decision and information tools. One important issue in this direction is to take into account the consequences of ~~DSSs and DISTs (~~decision and information support tools~~)~~ on the behavior of individuals and organizations (McIntosh, 2011). This implies that user assessment information, system dynamics and process feedbacks have to be included into the design of such tools. In Laniak et al. (2013) the current state-of-the-art and future directions for the discipline of integrated environmental modeling are extensively discussed. McIntosh et al. (2011) and Van Delden et al. (2011) propose theoretical methods and best practices for developing DSSs. In particular, these three studies emphasize both an iterative design and a development process that enable social learning of the different groups involved, such as users, scientists and IT-specialists. Moreover, ~~feedback loops throughout the process ensure social learning and a well-balanced DSS. As will be clear in the following sections, this approach is in very good agreement with the one proposed in this paper. Indeed, the aspects underlined here are mainly related to~~ they underline the application of correct methodologies in the process of DSS development, including definition of the scope, choice of suitable pre-existing or *ad-hoc* models, bridging science and policy gaps, and implementation making use of language appropriate to the end-users. ~~Finally, it is advisable that all steps take into account the presence of feedbacks allowing to improve the adhesion to the real context as well as the flexibility for future use.~~ As will be clear in the following sections, the above mentioned guidelines are in very good agreement with the approach proposed in this paper.

~~In the following, we briefly review some DSS tools integrating multicriteria and robustness analysis into model-based approaches for costal lagoon management. The reader is referred to, e.g., ProGEA (2004); Jakeman et al. (2008); Marcomini et al. (2009) for a broader overview of DSSs for water management.~~

~~In Pastres et al. (2001), a multicriteria approach for the choice of the area to be dedicated to extensive aquaculture in a coastal basin, is proposed. The developed DSS, based on a 3D spatial model, shows that the more suit-~~

~~able area for the rearing of *Tapes philippinarum* clams can be identified by combining spatial information (e.g., depth, area of distribution, healthiness), with an assessment of the potential productivity of the ecosystem.~~

~~Bayesian networks have been developed for four catchments in Europe as part of the MERIT Project (Management of the Environment and Resources using Integrated Techniques). The resulting model-based DSS allowed a range of different factors to be linked together, including natural resources management, stakeholders contribution, decisions and uncertainties (Bromley et al., 2005).~~

~~The MULINO-DSS (MULti-sectoral, INtegrated and Operational Decision Support System for Sustainable Use of Water Resources at the Catchment Scale) is a DSS that addresses complex decision problems dealt with in water resource management (Myšiak et al. 2002, 2005). The system was designed to integrate in a multicriteria framework socio-economic and environmental models developed for the Venice lagoon watershed (north-eastern Italy) by taking into account spatial dimension through the use of a Geographic Information System (GIS).~~

~~The mDSS4 (Giupponi et al., 2008), is finalized to assist water authorities in the management of water resources by improving their capacity to carry out a harmonized IWRM approach.~~

~~The STRIVER project (Strategy and methodology for improved IWRM - An integrated interdisciplinary assessment in four twinning river basins) placed emphasis on specific problems occurring in the basins which include trans-boundary water governance, environmental flows, water pollution, land-water use interactions and stakeholder participation (Gooch and Stålnacke, 2010).~~

~~Recently, the need for developing decision support based on a concrete participation of stakeholders has led to promote the integration of scientific and policy approaches with citizens' active involvement in the management of water resources (Pahl-Wostl, 2010; Viaroli et al., 2012).~~

Main keywords for the design of an effective model-based DSS for environmental applications are *integration*, *participation* and *modelling*. An interdisciplinary assessment integrating scientific knowledge, decision making and stakeholder participation is described in Gooch and Stålnacke (2010) for the case of river basin management. Giupponi et al. (2008) provide a decision support framework for participatory decision making processes in various fields related to the environment. The proposed approach is aimed at facilitating both the integration of environmental, social, and economic concerns and the involvement of interested parties in the formulation of strategies and decisions. Recently, the need for developing decision support based on a concrete participation of stakeholders has led to promote the integration of scientific and policy approaches with citizens' active involvement in the management of environmental resources (Pahl-Wostl, 2010; Viaroli et al., 2012). Public participation in environmental assessment and decision making is addressed in Dietz and Stern (2008), where merits and failings of participation are addressed. Among other recommendations, this study reports that efforts to integrate science and public participation are more likely to produce satisfactory results if they follow specific principles such as availability of decision-relevant information, explicit description of analytic assumptions and uncertainties, and iteration/feedback. These principles are also at the basis of the approach proposed in the present paper, where mathematical models of the system under study are integrated in an easy-to-use multicriteria decision making framework. Focus on the use of models in planning and management of transitional waters is put in Myšiak et al. (2002, 2005), where the DSS is designed to integrate in a multicriteria framework both socio-economic and environmental spatial models developed for the Venice lagoon watershed. A DSS based on a 3D spatial model is proposed in Pastres et al. (2001) for assessing the potential productivity of rearing of *Tapes philippinarum* clams in an Italian lagoon ecosystem. A similar application to clam farming is proposed in this paper.

For a broader overview of DSSs for water management the reader is referred to, e.g., ProGEA (2004); Jakeman et al. (2008); Marcomini et al. (2009).

3. The DITTY-DSS

In this section, some preliminary notations and definitions are firstly introduced, and then the architecture of the proposed DSS (in the following referred to as DITTY-DSS) is described.

3.1. Definitions

This section points out the terminology used in the paper to describe the proposed DSS. To ease the reader's understanding, we provide examples of each term from the real application described in Section 4.

The *system* is the part of the real world (environment, people, activities, etc.) that is the object of the decision maker's interests and actions (e.g., a lagoon ecosystem)[1]. It is assumed that the decision problem concerning the system is structured and presented in terms of *control options*, *criteria* and *constraints*.

Control options represent the alternative actions, strategies, and/or policies that can be set about to affect the system behavior (e.g., increasing the area of the lagoon dedicated to aquaculture). They are described by value assignments of the *controllable variables* (e.g., the amount of lagoon surface devoted to aquaculture). It is assumed that the system reacts to given values of the controllable variables (the causes) by changing the values of a set of *dependent variables* (the effects). For instance, if the area of the lagoon dedicated to aquaculture is increased, this affects the quantity of harvested clams.

Criteria are the rules or principles for evaluating the system performance induced by each possible assignment of controllable variables. For a quantitative assessment, criteria are expressed by means of *indicators*, represented by or computed from system dependent variables. For instance, the income from selling of clams (which depends on the quantity of harvested clams) can be used as an indicator related to an economic criterion. *Objectives* express the type of optimization to be performed on each indicator in form of either maximization or minimization (e.g., stakeholders aim at maximizing the income from selling of clams).

Finally, *constraints* are used to establish bounds for some/all the indicators and variables in order to discard unacceptable alternatives. They may reflect both physical and practical constraints, or correspond to thresholds defined on the basis of regulations and/or experience. For instance, a maximum value for the surface dedicated to aquaculture could be set in order to not interfere with other activities carried out in the lagoon.

A fundamental role for a reliable evaluation of the system performance under different control options is played by *uncontrollable variables*. These describe external (often unpredictable) factors that are not subject to choice, but do affect system dependent variables and indicators. For instance, weather conditions and water inflows into the lagoon are uncontrollable variables which influence the quantity of harvested clams, and therefore (as well as the market prices) the income from selling of clams. Even for a fixed control

[1] The system is to be distinguished from the DSS, i.e., the tool for supporting the decisions.

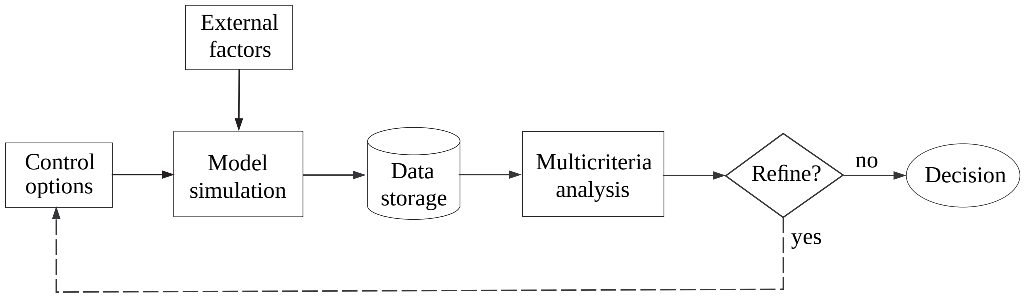

Figure 1: High-level block scheme of the proposed model-based DSS.

option, different realizations of uncontrollable variables may lead to different system performance. As a consequence, uncontrollable variables represent a source of uncertainty for the DSS output. Afterwards, it will be shown how this uncertainty is handled in the proposed DSS architecture and communicated to the decision maker.

3.2. DSS architecture

The scheme of the proposed model-based DSS is shown in Figure 1. It can be seen (feedback branch in Figure 1) that reaching the final decision is in general an iterative process, where at each iteration the solution from the previous iteration can be refined and improved. The different component blocks of the DSS and the steps performed in each single DSS iteration are now described in detail.

3.2.1. Control options

The block "Control options" generates the alternative control options (pre-existing or generated on demand) by assigning different values to the controllable variables. A discrete approach is assumed, where a finite (possibly very large) set of alternatives is considered. The generation mechanism is not specified, since it is strictly dependent on the application. As an example, if the controllable variable is the amount of lagoon surface dedicated to aquaculture (hence, a continuous variable), the block "Control options" may return a uniform grid of values in a specified interval. In other applications, the control options might be discrete by nature (e.g., installing or not a water purification plant at a given location).

Assuming that N different alternatives are generated, the value assignment to the controllable variables in the nth alternative is denoted by $v^{(n)}$,

$n = 1, \ldots, N$. It is assumed that $v^{(n)} \in \mathcal{V}$, where $\mathcal{V}$ is the set of all possible value assignments for controllable variables. Note that the discrete approach does not guarantee global optimality, so that the smaller the set $\{v^{(1)}, \ldots, v^{(N)}\}$ to choose from, the less likely it will contain a solution close to be optimal. On the other hand, for continuous sets $\mathcal{V}$, this can be the only possible approach in practice. These considerations imply that the decision maker should always attempt to generate the largest possible number of alternatives. In this respect, the feedback mechanism can be of help in order to focus the generation of the alternatives in the most promising zone of $\mathcal{V}$.

3.2.2. External factors

The block "External factors" generates values for the uncontrollable variables describing the external factors that cannot be controlled/manipulated by the decision maker, but do affect the system performance, and therefore are required for forming a reliable decision. Indeed, ignoring the uncertainty on external factors could invalidate the results of the study. As for the generation of control options, a discrete approach is assumed, where a finite set of assignments to uncontrollable variables is considered. The generation mechanism is again not specified, since it is strictly dependent on the application. Gridding is a possible way in case of continuous variables. In many applications, uncontrollable variables are discrete by nature, e.g., a binary variable representing whether a third party undertakes a given action or not.

Assuming that M different value assignments for uncontrollable variables are generated, the mth value assignment is denoted by $u^{(m)}$, $m = 1, \ldots, M$. It is assumed that $u^{(m)} \in \mathcal{U}$, where $\mathcal{U}$ is the set of all possible value assignments for uncontrollable variables. In general, it would be advisable to generate a set $\{u^{(1)}, \ldots, u^{(M)}\}$ as large as possible, in order to increase the confidence in the final decision induced by a detailed consideration of uncertainty.

3.2.3. Model simulation

The proposed DSS falls into the category of *model-based* DSSs (Power, 2002), i.e., DSSs integrating different kinds of mathematical and analytical models. Consequently, the block "Model simulation" represents a suitable interconnection of the models used to the following purposes:

- Simulate and predict the system behavior. The models adopted here should describe the cause-effect relation between independent (both controllable and uncontrollable) variables and dependent variables. For instance, in the running example related to clam farming in a lagoon, a biogeochemical model is used, receiving as inputs the amount of lagoon surface dedicated to aquaculture (controllable variable), meteorological variables and water inflows into the lagoon (uncontrollable variables), and providing as outputs the quantity of harvested clams, the concentration of oxygen and nutrients, etc. (dependent variables).

- Compute the performance indicators for a quantitative assessment of the evaluated control options.

Note that the block "Model simulation" can be seen as a mapping $\mathcal{M}$ from the inputs $\big(v^{(n)}, u^{(m)}\big)$ to the output $y^{(n,m)}$:

$$y^{(n,m)} = \mathcal{M}\big(v^{(n)}, u^{(m)}\big), \tag{1}$$

where $y^{(n,m)}$ is a r-dimensional vector containing the values of the r scalar indicators representing the system performance under the inputs $\big(v^{(n)}, u^{(m)}\big)$. Since all possible combinations of the inputs $v^{(n)}$ and $u^{(m)}$ must be evaluated, the total number of simulations performed at this step of a single DSS iteration is $N \times M$. Constraints imposed on the indicators, as well as on the dependent variables, are checked during each simulation. If one or more constraints are violated, the considered alternative is discarded as infeasible.

Remark 1. It is well known that mathematical models are never exact descriptions of a given system due to, e.g., uncertainty on model parameters or unmodeled dynamics. Therefore, the use of models adds a further source of uncertainty, together with external factors, which affects the DSS outcomes. The two types of uncertainty mix in the model outputs in a way which is difficult to distinguish. For this reason, in this paper we adopt an approach often used in control theory (Zhou et al., 1996), i.e., we consider the model uncertainty completely reflected in the uncontrollable variables. In other words, the model is considered free of uncertainty, while the uncontrollable variables vary in a set $\mathcal{U}^*$ which is possibly larger than the true set $\mathcal{U}$, and is chosen so as to reproduce the variability of the model outputs when $u_m \in \mathcal{U}$ and the model varies in its uncertainty set. Other approaches to uncertainty can be found in DSSs designed for environmental applications, e.g., Bayesian networks are developed in (Bromley et al., 2005) for four catchments in Europe.

Remark 2. An indicator may be in some cases the synthesis of a vector of values representing the dynamics of a variable of interest over time. The definition of a scalar indicator from a vector of values can be sometimes straightforward, whereas in other cases it can be troublesome and can be reliably done only under the guidance of the decision-makers. For example, a model may provide as output the daily cash flows during the year, and a meaningful economic indicator is simply the sum (possibly averaged) of the daily cash flows. On the other hand, if the oxygen concentration in the lagoon is the output of the model, then an indicator of possible interest for stakeholders is to count how many times over the year the oxygen concentration drops under a given anoxic crisis threshold.

3.2.4. Data storage

The block "Data storage" represents the data structure where the outputs of the block "Model simulation" are stored. More in detail, for fixed external factors $u^{(m)}$, the values of the performance indicators $y^{(n,m)}$ corresponding to the N evaluated control options are stored in the $N \times r$ matrix

$$I^{(m)} = [\ y^{(1,m)}\ \dots\ y^{(N,m)}\ ]^{\top}, \tag{2}$$

where the superscript $^{\top}$ denotes matrix transpose. After all $N \times M$ model simulations have been completed, the data stored in the matrices $\{I^{(1)}, \dots, I^{(M)}\}$ are used as inputs to the subsequent multicriteria analysis step.

3.2.5. Multicriteria analysis

For fixed external factors $u^{(m)}$, if only the jth criterion is considered ($j = 1, ..., r$), the best control option can be simply selected by taking the optimum over the jth column of (2). However, when r criteria are considered, it is 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. A variety of algorithms to solve multiple-criteria decision problems has been developed during recent decades. The interested reader is referred to Figueira et al. (2005) 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.

In this paper, a multicriteria analysis tool is considered as a mapping $\mathcal{A}$ from the indicator matrix $I^{(m)}$ to the N-dimensional score vector $s^{(m)}$:

$$s^{(m)} = \mathcal{A}\big(I^{(m)}\big). \tag{3}$$

Without loss of generality, the score vector is assumed to contain normalized values between 0 and 1. The higher the score, the better the trade-off performance of the evaluated control option with respect to the considered criteria. Therefore, the score vector defines a ranking of the control options, and the best control option (for fixed external factors $u^{(m)}$) should be selected by taking the maximum value in $s^{(m)}$.

In the application reported in Section 4, the adopted multicriteria analysis tool is the Analytic Hierarchy Process (Saaty, 1980), but the use of different tools, such as for instance, Reference Point (Wierzbicki, 1998) or ELECTRE (Roy, 1991) methods, is also possible. Note that each method may potentially ~~lead to~~ identify different best trade-off alternatives, and the choice of the methodology is subjective and dependent on the decision maker's preferences. While most of these tools usually include an internal mechanism for checking the robustness of the decision they produce (e.g., with respect to the user's choices), in the DITTY-DSS structure additional robustness analysis is carried out with respect to the external sources of uncertainties, namely all the system inputs that are not controllable by the decision maker. This is described in the next paragraph.

3.2.6. Decision

The block "Decision" represents the actual decision made by the decision maker based on the results of the multicriteria analysis. As discussed in the previous paragraph, if a single set of external factors $u^{(m)}$ is considered, the decision simply corresponds to the control option with maximum score in (3). On the other hand, when multiple sets of external factors $\{u^{(1)}, \ldots, u^{(M)}\}$ are considered, it is unlikely that the same control option turns out to be the best under all external conditions. For this reason, the DSS should provide a decision which is as robust as possible with respect to the variability of the external factors. This uncertainty on the DSS outcomes (induced by the uncertainty on the external factors) is taken into account by treating the scores of the control options provided by the multicriteria analysis as random variables, as described in the following.

Let $s_n^{(m)}$ denote the score of the nth control option under the mth set of external factors (i.e., the nth element of the vector $s^{(m)}$). For a fixed control option described by $v^{(n)}$, the set $\{s_n^{(1)}, \ldots, s_n^{(M)}\}$ describes the variability of the performance of the control option over the external factors $\{u^{(1)}, \ldots, u^{(M)}\}$. If we consider the score of the nth control option as a random variable S_n, the set $\{s_n^{(1)}, \ldots, s_n^{(M)}\}$ can be interpreted as a set of M realizations of the random variable S_n. This allows for any type of statistical analysis to be performed on the random variables $\{S_1, \ldots, S_N\}$. For instance, for each random variable S_n one could compute the sample mean:

$$\bar{s}_n = \frac{1}{M} \sum_{m=1}^{M} s_n^{(m)}, \tag{4}$$

and make the decision according to the ranking of the values $\{\bar{s}_1, \ldots, \bar{s}_N\}$. It goes without saying that one could devise more sophisticated selection rules based not only on the sample means, but also on other sample statistics of the random variables $\{S_1, \ldots, S_N\}$. Uncertainty on the DSS outcome could be communicated to the decision maker also pictorially by showing the empirical probability density functions of those random variables.

3.2.7. Feedback mechanism

A *feedback* mechanism allows the decision maker to extend or adapt the set of control options according to his/her preferences and the multicriteria analysis. Indeed, analysed solutions typically bring a deeper insight and understanding of what the problem actually is, and how it could be better solved. Therefore, the decision process is often an iterated procedure in which several runs of the DSS are performed, and the set of evaluated control options is better defined and refined as the decision maker acquires knowledge on the problem. In the running example related to clam farming in a lagoon, one could start from a uniform sampling of the interval of admissible values for the lagoon surface dedicated to aquaculture. Then, after each DSS iteration, one could exploit the feedback mechanism to generate control options with a denser sampling in the most promising subinterval. The process stops when the considered subinterval is sufficiently small.

4. Experimental results on the Sacca di Goro lagoon

In this section we describe the application of the DITTY-DSS structure to a real decision problem 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. The decision problem is concerned with the grant of new concessions for clam farming in the lagoon. However, since shellfish farming activities are responsible for important ecosystem disruptions, it is expected that increasing the farming area may result into a worsening of the ecosystem health. Hence, the aim of the developed DSS is to help the local authorities in finding a solution which guarantees a suitable trade-off between socio-economic interests and environment preservation.

Table 1: Definition of the decision problem 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	–

4.1. Definition of the decision problem

The decision problem of interest is summarized in Table 1. The only possible action available to the decision maker concerns the amount of hectares of new concessions to be granted to clam farmers. The solution is constrained in the interval [1300, 1450] ha, where 1300 ha corresponds to the current allocated area, while 1450 ha is the maximum extension the administrators estimate as feasible. Three indicators 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 revenue from aquaculture to boost the economic development of the area.

- The Lagoon Water Quality Index (LWQI) (Viaroli et al., 2005) expresses a pure environmental criterion related to water quality. Local

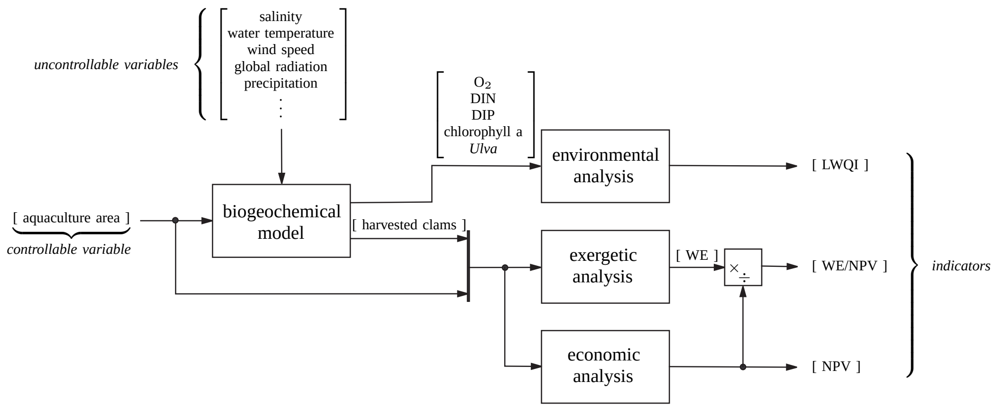

Figure 2: Internal structure of the block "Model simulation" in the application of the DITTY-DSS structure to the Sacca di Goro lagoon case study.

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 (Verdesca et al., 2006) 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.

4.2. Models

The internal structure of the block "Model simulation" in the proposed application is disclosed in Figure 2. It shows the models used, and the flow of all the signals from inputs to outputs. 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 assessing the performance of the simulated alternative.

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

4.2.1. Biogeochemical model

The 0D biogeochemical model of the Sacca di Goro lagoon proposed in (Zaldìvar et al., 2003) is used for dynamic simulation of the main biological,

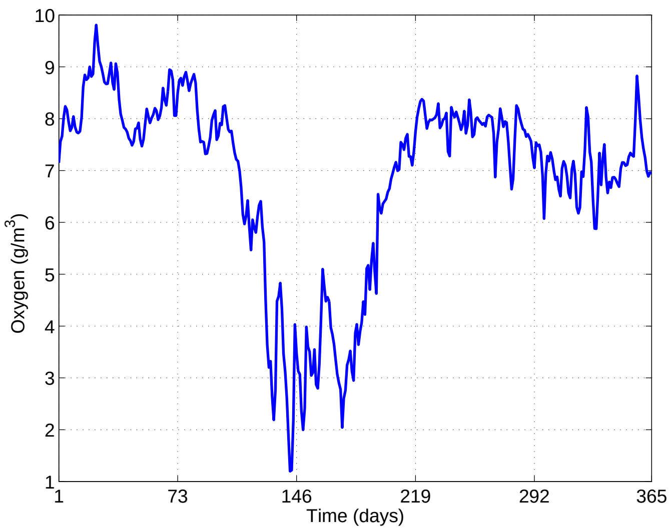

Figure 3: Oxygen dynamics simulated by the biogeochemical model of the Sacca di Goro lagoon under "dry" external conditions and 1350 ha aquaculture area.

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 listed in Figure 2. The time resolution of the model is daily, while the length of the simulations is determined by the length of the time profiles of the uncontrollable inputs (typically, a multiple of one year). Figure 3 shows an example of output from the model: the oxygen dynamics in a one-year simulation under external conditions measured in a dry year. Anoxic crises (deficiency of oxygen) are particularly evident in late spring.

4.2.2. Economic analysis

The NPV represents the aquaculture revenue, and is computed over the time horizon chosen by the user as the difference between benefits (the income from the sale of clams) and costs (e.g., salaries, costs for dredging and harvesting, etc.). In general, benefits are proportional to harvested clams, while costs are proportional to both aquaculture area and harvested clams.

In the proposed application, the time horizon is two years.

4.2.3. Environmental analysis

The LWQI proposed in (Viaroli et al., 2005) is based on the WQI of the National Sanitation Foundation, and on the standards of the Organisation for Economic Cooperation and Development. 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

$$\mathrm{LWQI} = \sum_{j=1}^{6} w_j \, f_j(x_j), \tag{5}$$

where w_j are nonnegative weights which sum up to 1, and $f_j(\cdot)$ is a suitable value function transforming the indicator x_j into a quality index between 0 and 100. For this case study, the weight vector w has been set to

$$w = [0.12,\ 0.12,\ 0.15,\ 0.15,\ 0.23,\ 0.23]^T.$$

The plot of the LWQI corresponding to the above mentioned one-year simulation is shown in Figure 4. By comparing it with Figure 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 LWQI is averaged over the length of the simulation. 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.

4.2.4. 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 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 (Verdesca et al., 2006). It can

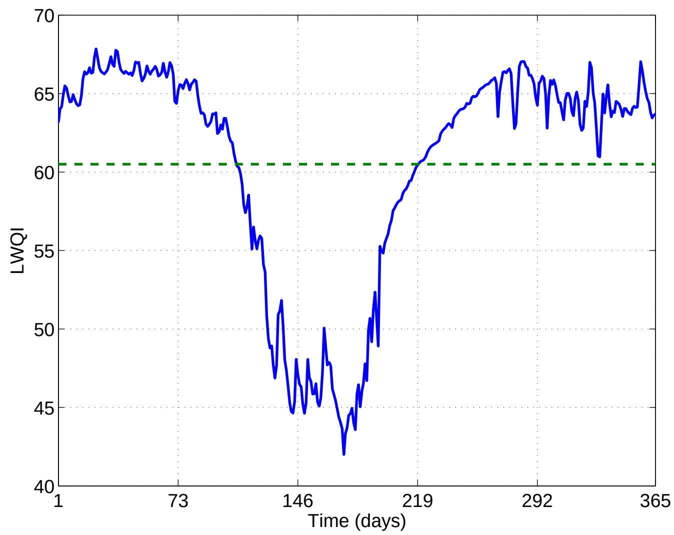

Figure 4: Plot of the LWQI computed using oxygen (see Figure 3), DIN, DIP, and chlorophyll-a concentrations, as well as macroalgae coverage, provided by the biogeochemical model of the Sacca di Goro. The dashed line represents the average LWQI value over one year.

be interpreted as the amount of ecosystem "health" lost per unit of revenue. Hence, the smaller the ratio WE/NPV, the more sustainable the production activities for the environment.

4.3. Multicriteria analysis

In this application the adopted multicriteria analysis tool is the Analytic Hierarchy Process (AHP) proposed by Saaty (1980). 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.

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.

4.4. Software interface

To allow for a deep analysis of each single step of the decision process and of the DSS outcomes, two graphical interfaces have been developed using the Matlab GUI. The first one is devoted to the step-by-step execution of the DSS components for a single assignment of control options and external conditions, while the second one implements a complete DSS iteration where a certain number of different value assignments to control options and external conditions are considered. The only component that was not developed in Matlab is the executable file of the biogeochemical model of the Sacca di Goro lagoon, which was provided by courtesy of the authors of the paper (Zaldìvar et al., 2003). All the plots of system variables, indicators and DSS outcomes shown in this section were generated using the developed user interfaces.

4.5. Results

This section presents two different types of results showing 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 step 25 ha, are initially evaluated and compared. The presented results are obtained by varying the criteria weights for fixed external factors in order to show the ability of the DSS to model the preferences and the objectives of end-users. Then, for fixed criteria weights, different value assignments to external factors are considered in order to show how uncertainty is managed in the proposed DSS. The aim is to select a control option that is robust with respect to varying climate conditions. At the end of this section, it is also shown how to exploit the feedback branch in Figure 1 in order to refine the solution provided by a previous DSS iteration.

4.5.1. Varying the criteria weights

The biogeochemical model of the lagoon is simulated over a time horizon of two years with seven different values of the aquaculture area. Non-extreme weather conditions are assumed in all simulations. The plots of the performance indicators (NPV, WE/NPV, and LWQI) are shown in Figure 5, where the ~~system nonlinear~~ nonlinear system behavior is apparent. Different weights for the criteria are generated by the AHP~~ are the following~~:

$$w_1 = [0.1062,\ 0.2605,\ 0.6333]^T\ , \qquad w_2 = [0.6333,\ 0.2605,\ 0.1062]^T.$$

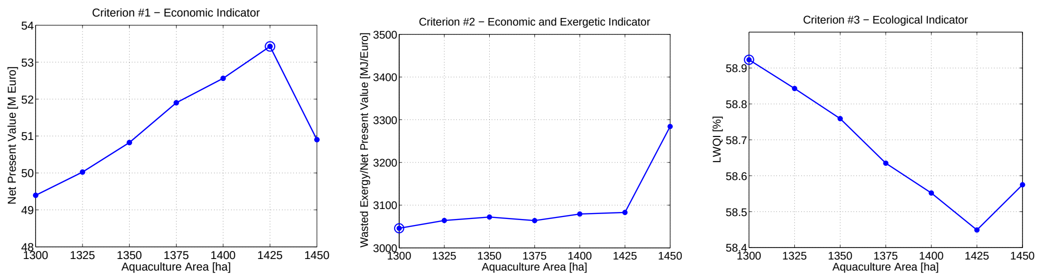

Figure 5: Plots of the performance indicators (NPV, WE/NPV and LWQI) versus the aquaculture area for normal weather conditions. The circled dot in each plot denotes the best option according to the corresponding criterion, among those evaluated.

Note that w_1 favours the environmental criterion (expressed by the third indicator, LWQI), while w_2 gives more weight to the economic criterion (expressed by the first indicator, NPV). The corresponding AHP scores are shown in Figure 6. By comparing Figure 5 and Figure 6, it is evident that the AHP is actually able to reflect the decision maker's preferences. Clearly, more complex situations can be devised by ~~setting appropriately~~ appropriately setting the decision maker's preferences.

4.5.2. Varying the external factors

The alternative control options corresponding to seven different values of the aquaculture area are again considered. The system performance corresponding to 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 figure out a control option which is optimal ~~in front of~~ under the uncertainty affecting the external factors. The vector of criteria weights w_2 is used in the AHP. For each external condition, the ~~scores associated by the AHP to~~ AHP scores associated with the different alternatives are reported in the rows of Table 2. 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 along the corresponding column, as described in Section 3.2.6. By comparing the

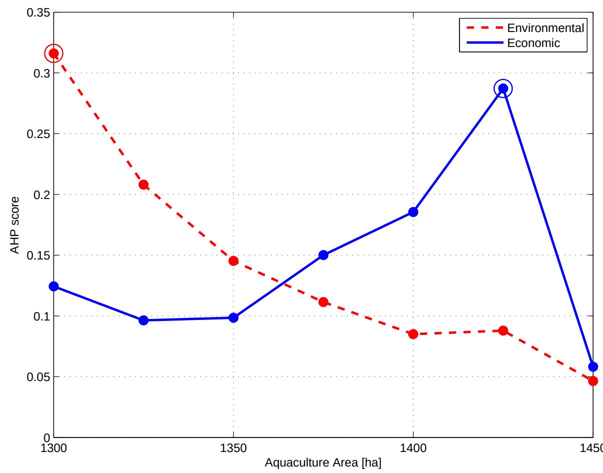

Figure 6: AHP scores obtained with different criteria weights for normal weather conditions. Solid: the economic criterion is favoured. Dashed: the environmental criterion is favoured. The circled dot in each plot denotes the best solution returned by the AHP.

last row of Table 2 with Figure 6 (dashed line), it can be seen that, when robustness issues are taken into account by considering the variability of the external factors, the solution settles at low values of the aquaculture area, even though the economic criterion is favoured. This suggests that, on average, the expected economic growth related to increasing the aquaculture area (and thus the clam production) does not compensate the environmental losses.

4.5.3. Refinement of the solution

The use of the feedback mechanism described in Section 3.2.7 is shown in this section through a simple example. Consider the setting of Section 4.5.1, where the external conditions are assumed to be fixed, and a grid of 7 control options with step 25 ha from 1300 to 1450 ha is considered in the first DSS iteration. Weights w_2 favouring the economic criterion are used in the multicriteria analysis. Observing Figure 6 (solid line), it is apparent that the solution with the highest score among those evaluated is 1425 ha, but, due to the discrete approach used, the true optimum could be nearby at a level not actually studied. For this reason, the decision maker may choose to refine the solution by running another DSS iteration where the evaluated control options are in the interval [1400, 1450] ha with step 5 ha, while external conditions and multicriteria analysis weights are not changed. The

Table 2: AHP scores under different external conditions. The highest score for any combination of weather conditions (D=dry, N=normal, W=wet) is highlighted in bold. Minimum, maximum and mean values for each alternative are also reported.

	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
min	**0.099**	0.096	**0.099**	0.037	0.032	0.036	0.031
max	0.311	**0.369**	0.351	0.283	0.214	0.287	0.031
mean	0.190	**0.201**	0.194	0.139	0.109	0.087	0.080

AHP scores obtained in the second DSS iteration are shown in Figure 7, and it can be observed that the solution corresponding to 1430 ha turns out to have a AHP score higher than 1425 ha. However, this does not mean that the decision maker would accept 1430 ha. From the analysis of Figure 7, it is apparent that 1430 ha is an edge value after which the performance degrades quickly. Therefore, the decision maker might decide to keep the solution ~~at~~ on lower values of aquaculture area (1425 ha or less) ~~in order to make it more robust~~ for a more robust decision with respect to uncertain factors not taken into account.

A similar approach could be used to refine the solution 1325 ha in the setting of Section 4.5.2 (see the last row of Table 2). Recall that, in this case, the AHP scores are averaged over different external conditions that must remain the same in all DSS iterations.

5. Discussion

In this section, we first show how the proposed DITTY-DSS framework can be used to describe different decision problems and how ~~it encompasses~~ several DSSs presented in the literature for specific applications fit in its general structure. Then, we critically review advantages and limits of the proposed framework, and finally we conclude the section by describing interactions with managers and decision makers.

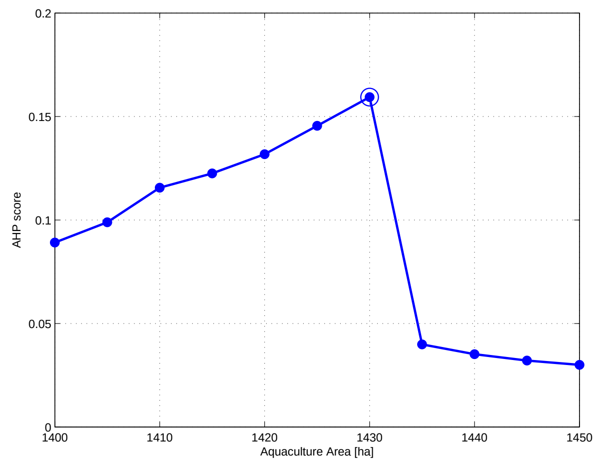

Figure 7: AHP scores obtained in the second DSS iteration using weights which favour the economic criterion.

Test sites of the DITTY project were the lagoons of Ria Formosa (Portugal), Mar Menor (Spain), Etang de Thau (France), Sacca di Goro (Italy), and Gera (Greece). Since each case study was characterized by different socio-economic and environmental characteristics, Table 3 presents the main features of the decision problems faced at each site, according to the terminology introduced in Section 3.1. Application to the Sacca di Goro lagoon has been described in detail in Section 4. A short description of the applications to the other DITTY test sites follows.

- In the Thau Lagoon, there are several shellfish farms and the control options are concerned with the localization of waste treatment plants in order to maintain the pollution level (*E.Coli*) under given safety thresholds while respecting a monetary budget constraint. Indicators to evaluate the control options describe both economic and environmental criteria. Uncontrollable variables represent different scenarios induced by future population growth.

- In the Gulf of Gera, local administrators need to plan future sustainable development of the area, and the decision problem is to choose which human activities should be boosted under budget constraints. Consequently, decision variables correspond to incentives accorded to activities such as tourism, agriculture (olives, greenhouses) and aquaculture. Considered criteria include economic and environmental aspects. Weather conditions are the uncontrollable variables of the problem.

- In Ria Formosa, decision makers consider increasing the area allocated to, and the density of clam farming. This should be done under the constraint of a sustainable development. Selected indicators describe pure and mixed economic and environmental criteria. Climate conditions act as uncontrollable variables and there are constraints on the maximum area allowed for clam farming.

- In Mar Menor, the decision problem consists in identifying cost-effective management actions able to reduce the nutrient loadings in the lagoon. No uncontrollable variables are considered since weather conditions and climate changes are not considered relevant or of interest. A monetary budget is available and several criteria (economic, environmental and social) are considered.

Table 3: Characteristics of DITTY sites

Site Name	Sacca di Goro	Etang de Thau	Gulf of Gera	Ria Formosa	Mar Menor
Problem	Request for new aquaculture concessions	Avoid oyster contamination	Allocate money	Decide area and density of shellfish	Cost-effective management options
Global objective	Sustainable development	Improve water quality	Sustainable development	Sustainable development	Reducing nutrient loadings
Criteria	Economic Environmental/Economic Environmental	Economic Environmental -	Environmental/Economic Environmental -	Economic Environmental Environmental/Economic	Environmental Economic Social
Controllable Variables	Size of area increase	Waste treatment plant location	Activities to stimulate	Area and density for shellfish farming	Management options
Uncontrollable variables	Climate conditions	Population growth	Climate conditions	Climate conditions	-
Constraints	Area	Budget	Eutrophication level	Area	Budget

Though the decision problems at the five DITTY test sites were to a large extent different, it is stressed that all of them were easily accommodated in the DITTY-DSS structure of Figure 1, thus confirming its flexibility and ease of use. This conclusion is strengthened by the fact that~~, quite remarkably,~~ several important DSSs developed for specific water management applications, such as Carvalho (2002) and Myšiak et al. (2005), fit in the general structure proposed in this paper. Hence, the structure described in Figure 1 can be considered as a unitary framework for ~~many DSSs already and to be designed~~ existing and future water management DSSs.

Another important feature of the high-level block structure of the DITTY-DSS, which is the result of an effort of simplification and abstraction, is that it makes the decision process from the definition of the alternatives to their comparative evaluation more transparent to stakeholders and to model developers (who might not have the know-how in the field of decision support and optimization), thus achieving two main benefits:

- ~~It calls the DSS development to drive~~ DSS development drives 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. On the contrary, the prior definition of the DSS structure focuses complementary steps such as data compilation, development of models and indicators, scenario analysis, etc., on the requirements of the DSS, thus ensuring that the information gathered is complete and relevant to the decision problem at hand.

- It enables a clear definition of communication protocols, data flows, interchange formats, inputs to and outputs from the models, etc. This modularity 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 in.

Summarizing, the main strengths of the proposed model-based DSS framework are twofold:

- Many application-specific DSSs can be found in the literature. These DSSs are often very powerful tools with a variety of functionalities and nice user interfaces, but typically are undisclosed to the users, who cannot gain confidence on a particular tool based on the knowledge of its internal structure. The proposed DSS framework provides an open, simple structure where all building blocks of a model-based DSS are disclosed and the sequence of activities composing the decision making process is clearly indicated. This goes in the direction of fulfilling the fourth guideline recalled in Section 1, since it enables awareness and understanding of the decision maker about the tools used.

- The proposed DSS framework may represent a useful guide to inexpert users in developing their own DSS. First of all, the general architecture of the DSS structure is not specifically tailored to coastal lagoon management problems, and is therefore directly applicable ~~in~~ to other decision problems arising in water resource management, or even in different domains. Whatever the application is, it enables a clear identification of variables and cause-effect relations, thus driving the choice of appropriate models and tools. Moreover, the modular structure allows for an easy update of the DSS as soon as new (e.g., more accurate or less time-consuming) versions of the models are made available. Finally, it makes the role of uncertainty on uncontrollable factors and models explicit, and provides a simple, statistical way to take into account the effects of uncertainty on the DSS outcomes.

Experience in the DITTY project taught us that both points of strength of the proposed DSS framework are effective in practice.

The main limitation of the proposed DSS framework is the discrete approach with respect to the control options and the external factors. When control options and external factors vary in continuous sets, gridding of these sets suffers from a number of drawbacks. First of all, there is no guarantee that the final decision is the truly optimal one, since evaluation of points outside the considered grid could in principle change the outcome of the decision process. This problem could be alleviated by increasing the density of the grid, but this solution is not always possible in practice, especially when model simulations are very time consuming. In this respect, another opportunity offered by the proposed DSS structure is to exploit the feedback branch for the refinement of the solution. One could start from a sparse grid of the set of control options, and then refine iteratively the solution in the most promising zone. Another limitation of the proposed DSS framework is that it heavily relies on the availability of models of the cause-effect relations in the system under study. If models with these characteristics are not available or cannot be developed, the DSS structure of Figure 1 is not applicable.

In this respect, another limitation is that the DITTY-DSS structure was not conceived for model development. Moreover, the accuracy of the DSS outcomes is strictly dependent on the accuracy of the models. ~~Though~~ Although model uncertainty is considered and presented in the DSS outcomes, inaccurate models ~~turn out into~~ produce a high level of uncertainty, thus hindering decision makers from trusting ~~in the results of the decision process~~ the DSS results. Finally, another limitation could be that the mechanism underlying the DSS structure of Figure 1 is not completely automatic, rather it requires user's participation and supervision ~~(e.g., to guide the refinement of the solutions)~~. ~~Though~~ Although participation of decision makers in the decision process is ~~often considered as~~ a prerequisite ~~in the development of~~ for developing effective DSSs, ~~in some cases too much~~ we experienced that their involvement in highly technical parts, such as guiding the refinement of the solutions or providing the AHP pairwise comparisons, could ~~turn out to be annoying, and~~ repulse ~~decision makers~~ them from using the tool.

To conclude this discussion section, we briefly outline some key points related to the interaction between the decision maker and the DSS.

- Experience of the decision maker is very important for the analysis of the DSS outcomes. When unexpected discrepancies between the decision maker's intuition and the DSS results are observed, the decision maker is led to explore the origins of those differences. Hidden causes could be either an inaccurate model, that therefore should be updated, or a systemic behavior that the manager was previously unaware of.

- Focusing the analysis in certain areas of the set of control options according to the decision maker's intuition, should be used with caution. If, on the one hand, it can help reducing the overall computational load of the decision process (since less DSS iterations are needed to reach the final decision), on the other hand it can bias the search far from regions that the decision makers wrongly believes to be unpromising.

- Limits on the maximum number of alternative control options to be evaluated cannot be set a priori, rather they depend on the available computational power and the multicriteria analysis method adopted. Typically, the computational time required for the "Model simulation" step scales linearly with the number of evaluated control options. On the other hand, when using the AHP as the multicriteria analysis tool, the number of pairwise comparisons that the decision maker should analyse scales quadratically. Therefore, the number of evaluated control options may be limited by the willingness of the decision maker to provide the pairwise comparisons.

6. Conclusions

In this paper, a general structure for model-based DSSs for water resource management has been presented. It allows integration of 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 with respect to stochastic external factors and model uncertainty 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. ~~Future research directions aim at the integration of GIS databases in the DSS structure, and its application to different decision problems.~~ An interesting future application consists in adding a Geographic Information System to the DSS, as is done in Myšiak et al. (2005). Indeed, the proposed DSS framework can be easily extended to accommodate spatially distributed models. Moreover, the application of the proposed DSS framework to a wider range of problems, including those arising in business and health care, will be considered.

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