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Sànchez-Marrè, Miquel; Comas, Joaquim; Rodríguez-Roda, Ignasi; Poch, Manel; and Cortés, Ulises, "Towards a Framework for the Development of Intelligent Environmental Decision Support Systems" (2008). International Congress on Environmental Modelling and Software. 221. https://scholarsarchive.byu.edu/iemssconference/2008/all/221

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Towards a Framework for the Development of Intelligent Environmental Decision Support Systems

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Abstract: Intelligent Environmental Decision Support Systems (IEDSS) are present in the environmental management process at different levels such as hazard identification, risk assessment, risk evaluation and intervention decision-making, but there is neither a well defined methodology nor a framework for the development of IEDSSs. The purpose of this paper is to provide a study on several approaches found in the literature to set-up a methodology and a plausible architecture for the development of IEDSSs. Also a general outlook into the classical decision making theories is done to provide a general and well based architecture. Taking into account the review of proposals, and some previous general architectures proposed by the authors, a new comprehensive architecture and associated methodology to develop an IEDSS for whatever domain is proposed. The methodology proposed and the architecture joins the main three cognitive tasks involved in a decision making process: analysis tasks, synthesis tasks, and prognosis tasks.

Keywords: Intelligent Environmental Decision Support Systems.

1. INTRODUCTION

Environmental Systems are usually very complex systems which are not easily managed. Environmental systems are stochastic and, very often, are multi-scale, spatial and temporal-dependent processes. They also tend to comprise complex interactions among physical, chemical and biological processes. These processes may not be known well and/or may be difficult to represent, causing considerable uncertainty. Some of the sources of this uncertainty can be tamed with additional data or further investigation, but this uncertainty becomes insurmountable especially when characterised by chaotic behaviour or self-organising processes.

Therefore, advocating a single perspective that encompasses everything in a system is becoming increasingly difficult and ineffective. The consensus is developing that environmental issues must be considered in terms of complex systems. But not all environmental systems present the same level of complexity in terms of both the degree of uncertainty and the risk associated with decisions. If the degree of complexity is represented as a function of uncertainty, on one hand, and the magnitude or importance of the decision, on the other hand, then we might distinguish three levels of complexity [Funtowicz and Ravetz 1993; 1999]:

- The first level of complexity would correspond to simple, low uncertainty systems where the issue at hand has limited scope. A single perspective and simple models would suffice to provide a satisfactory description of the system.
The second level would correspond to systems with a higher uncertainty degree where simple models can no longer provide satisfactory descriptions. Acquired experience then becomes more and more important, and the need to involve experts in problem solving becomes advisable.

Finally, the third level would correspond to truly complex systems, where much epistemological or ethical uncertainty exists, where uncertainty is not necessarily associated with a higher number of elements or relationships within the system, and where the issues at stake reflect conflicting goals. It is then crucial to consider the need to account for a plurality of views or perspectives.

In fact, these three levels of complexity are very similar to the original classification of different kind of problems proposed by H. A. Simon [1960]: structured, semi-structured and unstructured. These levels of complexity are depicted in figure 1.

![Diagram of DSS Domain and Kind of Problems](image)

**Figure 1.** Kind of problems following Simon’s proposal

In this sense, it is important to realise that environmental problems are characterized by dynamics and interactions that do not allow for an easy division between social and biogeophysical phenomena. Much ecological theory has been developed in systems where humans were absent or in systems where humans were considered an exogenous, simple and detrimental disturbance. The intricate ways in which humans interact with ecological systems have been rarely considered [Kinzig 2001]. Embracing a socioeconomic perspective implies accepting that all decisions related to environmental management are characterised by multiple, usually conflicting objectives, and by multiple criteria (Ostrom 1991). Thus, in addition to the role of experts, it becomes increasingly important to consider the role of wide public participation in the decision making processes. Experts are consulted by policy makers, the media, and the public at large to explain and advise on numerous issues. Nonetheless, many recent cases have shown, rather paradoxically, that while expertise is increasingly sought after, it is also increasingly contested [Ludwig 2001].

In the last decades, mathematical/statistical models, numerical algorithms and computer simulations have been used as the appropriate means to gain insight into environmental management problems and provide useful information to decision makers. To this end, a wide set of scientific techniques have been applied to environmental management problems for a long time and with good results.

But most of these efforts were focused on problems that could be assigned to the first level of complexity (i.e., simple, low uncertainty systems where the issue at hand has limited scope), following the classification of [Funtowicz and Ravetz, 1993; 1999]. Consequently, many complex environmental problems have not been effectively addressed by the scientific community. However, the effort to integrate new tools to deal with more
complex systems has led to the development of the so-called Environmental Decision Support Systems (EDSSs) [Guariso and Werthner, 1989],[Rizzoli and Young, 1997].

EDSSs have generated high expectations as a tool to tackle problems belonging to the second and third levels of complexity. Thus in a recent review of the relevant literature in the topic, more than 600 references were found (including journal articles, conference papers, and technical reports) during the 90s, with only 10 references in 1992 and more than 150 references per year towards the end of the decade. The range of environmental problems to which EDSSs have been applied is wide and varied, with water management at the top (25% of references), followed by aspects of risk assessment (11.5%) and forest management (11.0%). Equally varied are the tasks to which EDSSs have been applied, ranging from monitoring and data storage to prediction, decision analysis, control planning, remediation, management, and communication with society. Intelligent Environmental Decision Support Systems (IEDSS) are the envisioned new tools to cope with the inherent complexity of environmental problems [Sánchez-Marré et al., 2008]. Other traditional computational approaches do not seem to be enough flexible and capable to safely and successfully handle complex real-world environmental problems.

2. IEDSSs: ORIGINS AND PREVIOUS APPROACHES

Environmental issues belong to a set of critical domains where wrong management decisions may have disastrous social, economic and ecological consequences. Decision-making performed by EDSSs should be collaborative, not adversarial, and decision makers must inform and involve those who must live with the decisions. EDSS should be not only an efficient mechanism to find an optimal or sub-optimal solution, given any set of whimsical preferences, but also a mechanism to make the entire process more open and transparent. In this context, Intelligent EDSSs or IEDSS can play a key role in the interaction of humans and ecosystems, as they are tools designed to cope with the multidisciplinary nature and high complexity of environmental problems. In the following we shall describe the nature of IEDSS.

From a functional point of view, and taking into account the type of problem that the IEDSS solves, two kinds of IEDSS can be distinguished but of course most systems of interest fall between these two categories:

- The first category, which we could name as dynamic IEDSS, are those IEDSS which aim to control or supervise a process in real-time (or almost real-time), facing similar situations on a regular basis [Sánchez-Marré et al. 1996]. They must guarantee robustness against noise, missing data, typos and any combination of input data. In general the end-user is responsible for accepting, refining or
rejecting system solutions. This responsibility can decrease, thereby increasing IEDSS confidence, over time in as far as the system is facing situations that were successfully solved in the past (real validation).

- In the second category, which can be named as static IEDSS, there are those IEDSS that give punctual support to decision-making, and are mainly used to justify multicriteria decisions of policy-makers more than to make real decisions on a day-to-day basis [Comas et al. 2003]. Here it is interesting for the end-user to play with what-if scenarios, to explore the response surface and the stability of the solution; for example how sensitive our decision is to small variations in the given weight and value of the relevant variables. The role of socio-cultural and economic issues limits the use of standard databases. Confidence can not be increased in the results when facing similar situations, because these IEDSS are very specific and sometimes are only built to make or justify one decision.

2.1 Previous approaches

Decision theory is a field which has been studied long time ago from the perspective of business, economics and management sciences. One of the most well known decision making model was proposed by H. A. Simon [1960].

![Figure 3. Decision making model by Simon](image)

The three levels of decision process according to Simon are:

- Intelligence: at this level, there is the search for information and knowledge, in order to identify a problem requiring a decision-making task.
- Design: at this stage, the building and analysis of possible alternatives or strategies to solve the detected problem is done.
- Choice: the decisor selects one of the possible alternatives analyzed and generated in the previous step. The selected alternative satisfies the rational behaviour criterion. This means the selected alternative is the best one having in mind the fact that it provides the decisor with the maximum utility or benefit.

According to Fox and Das [2000], a decision support system is a computer system that assists decision makers in choosing between alternative beliefs or actions by applying knowledge about the decision domain to arrive at recommendations for the various options. It incorporates an explicit decision procedure based on a set of theoretical principles that justify the “rationality” of this procedure. Thus, an intelligent information system reduces the time in which decisions are made in a domain, and improves the consistency and quality of those decisions [Haagsma and Johanns 1994].

Thus IEDSSs could be defined [Sojda 2002] as systems using a combination of models, analytical techniques, and information retrieval to help develop and evaluate appropriate
alternatives [Adelman 1992; Sprague and Carlson 1982]; and such systems focus on strategic decisions and not operational ones. More specifically, decision support systems should contribute to reducing the uncertainty faced by managers when they need to make decisions regarding future options [Graham and Jones 1988]. Distributed decision making suits problems where the complexity prevents an individual decision maker from conceptualizing, or otherwise dealing with the entire problem [Boland et al. 1992; Brehmer 1991]. Other definitions could be found in D’Erchia et al. [2001].

Cortés et al. [2000] proposed an IEDSS architecture based on five steps (see Figure 4):

- The first step of the IEDSS (data interpretation) encompasses the tasks involved in data gathering and registration into databases. Original raw data are often defective, requiring a number of pre-processing procedures before they can be registered in an understandable and interpretable way. Missing data and uncertainty must be also considered in this level. Also, the knowledge discovery step including data mining techniques are included here providing the IEDSS with the environmental process knowledge.
- The second step, diagnosis level, includes the reasoning models that are used to infer the state of the process so that a reasonable proposal of actuation can be
reached. This is accomplished with the help of statistical, numerical and artificial intelligence models, which will use the knowledge previously acquired.

- The third step, decision support level, establishes a supervisory task that entails gathering and merging the conclusions derived from AI knowledge models and numerical models. This level also raises the interaction of the users with the computer system through an interactive and graphical user-machine interface. When a clear and single conclusion can not be reached, a set of decisions ordered by their probability or certainty degree should be presented to the user.

- In the fourth level, plans are formulated and presented to managers as a list of general actions or strategies suggested to solve a specific problem.

- The set of actions to be performed to solve problems in the domain considered are the fifth and last step. The system recommends not only the action, or a sequence of actions (a plan), but a value that has to be accepted by the decision maker. This is the final step in the architecture that closes the loop.

Decisions are made when a deviation from an expected, desired state of a system is observed or predicted. This implies a problem awareness that in turn must be based on information, experience and knowledge about the process. Those systems are built by integrating several artificial intelligence methods, geographical information system components, mathematical or statistical techniques, and environmental/health ontologies, and some minor economic components. Examples are the works by Dorner et al. [2007], Reichert et al. [2007] and Cortés et al. [2001]. This progression in complexity of the methods, and in the intensive use of knowledge usually required to develop an IEDSS, corresponds to an increase in data required to support the models (see Fig. 2, adapted from Wittaker [1993]).

3. A COGNITIVE-ORIENTED APPROACH FOR DEVELOPMENT OF IDSSs

Taking into account the different approaches for the development of IEDSS proposed by several authors, there is the need for a common framework to develop an IEDSS either it is a static IEDSS or a dynamic IEDSS.

Studying the several proposals and taking into account the main cognitive tasks of human beings within the decision-making environment, the common underlying tasks in most of IEDSS can be extracted. The following general architecture is proposed for IEDSS. It is based on a three-layer architecture:

- **Analysis tasks**: In this layer is where most of interpretative processes are run. At this stage the data gathering processes as well as the knowledge discovery process by means of some data mining techniques are undertaken to get diagnostic models. These models will provide the IEDSS with hard analytical power to get an insight of the environmental system/process being supervised in real-time or managed in an off-line basis. Most of these techniques come from the data mining field.

- **Synthesis tasks**: This layer wraps all the work necessary to synthesizes possible alternative solutions for the different diagnostics found in the previous step. This synthesisisation can be done through several solution generation methods based on Statistical techniques, on Artificial techniques or on Mathematical/Numerical techniques. Of course the integration of different nature methods could enhance the problem solving ability of the IEDSS.

- **Prognosis tasks**: At this upper layer relay the inherent ability of IEDSS to decision support tasks. At this level, the several predictive models, which can be numerical (mostly simulations) or rather qualitative (qualitative reasoning or qualitative simulations), are used to estimate the consequences of several actions proposed in the previous step by the solution generation methods. These “what if” models let the final user/decisor to make a decision based on the evaluation of
several possible alternatives. At this stage, the temporal and spatial features could be very important for a good environmental modelling practice.

These three-layer architecture is depicted in figure 5.

**Figure 5.** The cognitive-oriented approach for IEDSS development

### 4. CONCLUSIONS

IEDSS can play a key role in the interaction of human beings and ecosystem, as they are tools designed to cope with the multidisciplinary nature and high complexity of environmental problems. IEDSS help in the design of understandable, credible, and easily accessible information systems that are necessary to improve our still incomplete knowledge and understanding of the ecosystem.

Decisions are needed to manage complex environmental systems. This implies a problem awareness that in turn must be based on information, experience and knowledge about the process. IEDSS are built by integrating several artificial intelligence methods, geographical information system components, mathematical or statistical techniques, and environmental/health ontologies, and some minor economic components.

Although there are some architecture proposals found in the literature to combine all this techniques and knowledge, there is not a common framework to be taken into account as first guideline to deploy both static and dynamical IEDSS.

In this paper, a new cognitive-oriented architecture has been proposed, with three main cognitive tasks as a common framework for IEDSS. This architecture is wrapping both the emphasis of static IEDSS, which relies in the second and third layer, and the dynamical IEDSS, which commonly focus on the first and second layers.
This approach has been used in the development of a wastewater treatment plant supervisory system as described in [Poch et al., 2004].

ACKNOWLEDGEMENTS

The authors wish to thank the partial support of Spanish project TIN2004-01368.

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