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A modelling platform for complex socio-ecosystems: an application to freshwater management in coastal zones

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Abstract: Providing deliberation support tools for freshwater management in coastal zones requires complex socio-ecosystem modelling in a joint effort from research scientists, software engineers and stakeholders. The SPICOSA System Approach Framework provides guidelines for the building of dynamic models for a better comprehension of the variety of processes and issues regarding coastal management. A modular platform was developed using the ExtendSim® software. We explore how the SPICOSA/Extend platform supports participatory modelling by offering the necessary tools for the integration of multidisciplinary knowledge and how the use of a common platform facilitates dialog between research scientists of varied backgrounds. Graphical tools developed in ExtendSim allow for a synthetic and user-friendly representation of the system processes and, in particular, of performances of management options in prospective scenario simulations.
We discuss how an economical and social approach of the issues influences the choice of processes and variables to be modelled as well as the level of complexity needed to represent the ecological and physical system. The illustration of this approach will be supported by two case studies. The first concerns the freshwater use competition in the Charente River on the French Atlantic coast. The second refers to water quality management applied to micro-biological contamination from watershed runoff in the Thau lagoon on the French Mediterranean coast.

Keywords*:* Integrated assessment tools, socio-ecosystem modelling, ICZM, ExtendSim.

1. INTRODUCTION

SPICOSA (Science and Policy Integration for Coastal System Assessment) is an integrated European research project in support of ICZM (Integrated Coastal Zone Management). The project started in February 2007 and ends in January 2011 and encompasses 18 study site applications The SPICOSA project develops a System Approach Framework (SAF), which aims at incorporating the ecological, social and economic dimensions in order to support decision making in complex coastal systems.
Models for integrated assessment deal with extremely varied processes, approaches, scales and scientific domains. In this context, building predictive models is a highly time-consuming undertaking and often lacks the necessary data, knowledge and flexibility. Following Brugnach et al. [2008] model typology, system approach models must be built: (1) for exploratory purposes: to allow managers to test a high variety of policy options, (2)

for learning purposes: to integrate and share knowledge to deal with the complexity of issues facing the decision-makers in coastal areas [Westmacott, 2001].
We here present system approach guidelines for participatory modelling supported by our experiment in two case studies: (1) the Pertuis Charentais on the French Atlantic coast deals with fresh water use competition, (2) the Thau Lagoon, on the Mediterranean coast, refers to water quality management applied to micro-biological contamination from watershed runoff. The on going development of those two assessment models using ExtendSim software led us to formalise a building methodology in three main stages: cognitive system representation, model components development and outputs construction.

2. DEVELOPMENT TOOLS AND STUDY SITES

2.1 The ExtendSim modelling software

The SPICOSA project chose the ExtendSim software (www.ExtendSim.com) for its system modelling capacities inherited from STELLA type platforms (www.iseesystems.com) with an additional and essential feature of hierarchical decomposition of processes. It is designed for discrete or continuous modelling. It uses independent blocks set in drag-and-drop libraries and offers numerous modelling, graphical, input/output basic pre-programmed blocks. Data are passed from block to block using user designed connections. A very attractive feature of the software is the possibility of building "custom" blocks in ModL language (similar to C language) with a graphical interface for icon view, a dialog box for parameters and a "help" box for comments and documentation. Custom blocks are stored in user defined libraries allowing for modular development. A data base has been embedded in the software in version 7.0: a very useful commodity for parameter readability, storage of data and of outputs. The data base and the blocks can communicate with the EXCEL software. However, queries are heavy-handed and we had to establish user-friendly functions and nomenclature.

2.2 Quality protocol

Integrated socio-ecosystem modelling must be creative, disciplined and systematic and improves with participation of multiple actors: stakeholders, local managers, scientist and modellers [Jakeman et al., 2008]. All along the development process of the model, it is recommended to apply a quality control methodology. In the SPICOSA framework, we use a Design-Formulation-Appraisal (DFA) protocol. This iterative process should be applied at all levels and be approved (appraisal step) by consensus of the experiment participant group thus promoting a strong participatory involvement.

2.3 Two SPICOSA study sites: the Pertuis Charentais and the Thau Lagoon

Fresh water competition in the Pertuis Charentais:
Along the French Atlantic coast, the Pertuis Charentais coastal waters are strongly impacted by the Charente River. Two important industries in the area are dependent on freshwater availability: agriculture and shell fish farming. However, the river suffers from low flow in summer and shows a risk of failing the EU Water Framework Directive in sustaining drinking water for households and tourism as well as the local industries and a good ecological status of the coastal ecosystems. The policy issue for the study site was decided with a stakeholder group of six local managers and concerns the quantitative management of the freshwater in the Charente river watershed and its impact on the coastal waters. The objectives must be addressed following the regional management plans: hierarchy of freshwater uses and a target of Reachable Discharge Thresholds at chosen monitoring stations on the river in summer over the next 10 years.

Microbiological contamination of the Thau Lagoon:
The Thau Lagoon, situated in the west of the Mediterranean French coast, sees its water quality strongly impacted by a rapid demographic growth and by an important seasonal

influx due to tourism and failures in the water treatment system. The current political debate regards the ways the reduction of microbiological contamination of the lagoon could be translated into an operational policy objective, which will combine the sanitary classification of the Lagoon (A or B) and the occurrence of commercial bans for the shellfish farming industry. The SPICOSA Thau lagoon team has entered into a partnership with the local public organisation in charge of the Thau lagoon water management ("Syndicat Mixte du Bassin de Thau", SMBT) and is expected to supply scientific advice for the implementation of the local water management plan (SAGE).

3. System approach modelling guidelines

The construction process of the integrated model system is separated in three main stages:

- Cognitive system representation: a participatory investigation of the best representation of the system.
- Model components development: all the model components are mathematically formulated and implemented in ExtendSim with an objective of *a minima* level of complexity.
- Outputs construction: development of adapted visualisation and documentation tools for exploratory, learning and communication purposes.

3.1 Cognitive system representation

Participatory development of assessment tools for ICZM can be time consuming as it involves numerous people: stakeholders of different management agencies, scientists and engineers of different domains and institutes. It is however essential that stakeholders be strongly involved in the first design step [Voinov et al., 2008] to insure that the question asked and so the focus of the model corresponds to the need of end users [Westmacott, 2001] and will be useful as a deliberation support tool.

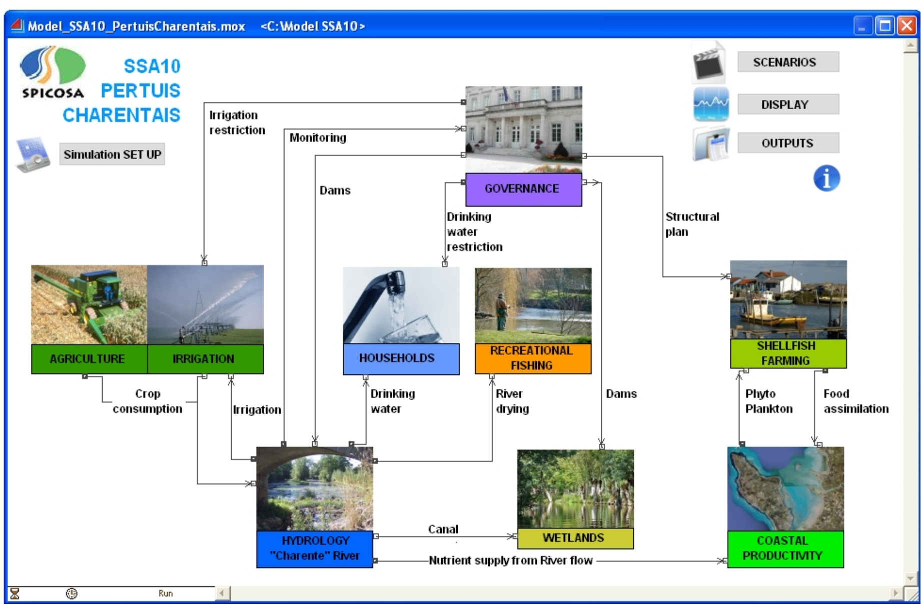

Figure 1. The Pertuis Charentais model

In a first step, using a DPSIR causal methodology, the different "actors" –modules– are identified within the three ecosystem services approach categories: "governance", "uses" and "resources". The ExtendSim software interface allows building of empty container hierarchical blocks, each with its own user defined icon representation. As shown on the Pertuis Charentais model interface (Figure 1), the blocks are organised according to the following classification: (1) on top, governance and regulation e.g. irrigation restrictions based on river water flow monitoring, (2) in the middle, environmental resources uses e.g. agriculture, drinking water for households, recreational fishing and shell fish farming, (3) on bottom, the resources systems e.g. the Charente river hydrology, wetlands and coastal water productivity.

Once the "actors" are identified, the second step consists of defining the vertical and transversal interactions with their corresponding indicators. Stakeholders are usually comfortable with defining their resources needs; however their possible downstream impact on other actors of the system –often unknown by the stakeholders themselves– must now be formulated. In the Pertuis Charentais system, the shell fish farming industry claims that summer low water flow from the Charente river in the coastal waters due to excessive irrigation diminishes their production and their spat collection activity. The model must therefore represent the claimed link between agriculture and shell fish farming through the hydrological system: the agriculture module collects water for irrigation from the river hydrology which is connected through a nutrient supply flux to a coastal productivity compartment. The shell fish farming module consumes the produced phytoplankton and feedback on coastal waters through this food assimilation (see Figure 1). For the governance modules, input link for monitoring of "resources actors" and output link for application of governance rules on "uses actors" are established.

In the third step of the cognitive representation, the modelling team has to look for internal feedback loops. Indeed, for the socio-ecosystem model to be dynamic, it must present such a feature. If no internal feedback loop can be established, the scope of the system or the "actors" definition must be broadened. This can be tested using Forrester [1971] representation of system dynamics (Figure 2).

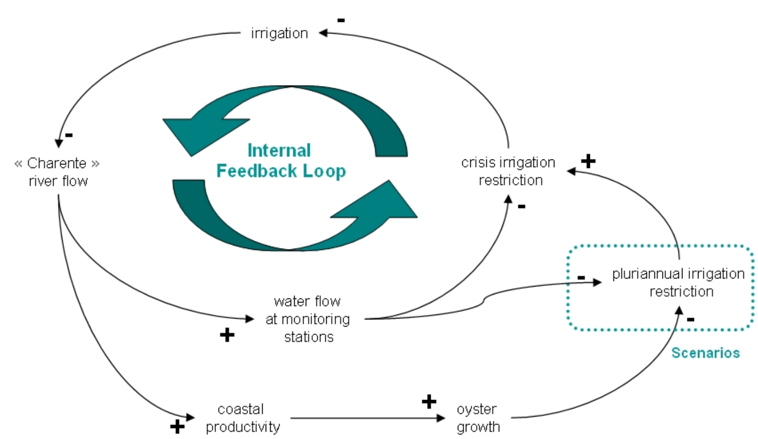

Figure 2. Representation of internal feed back loops (Pertuis Charentais system)

In the final step, the system representation has to be appraised by the participant group. At this stage, the common feedback we received was that the model clearly visualised the connections between the different components and showed each participant how their management sector was situated and interacted in the global coastal system. Furthermore, when showed to a panel of scientists specialised in the Marennes-Oleron bay ecosystem for review and discussion of existing knowledge and data, the model opened an integrative scientific discussion about the impact of the Charente river inputs for oyster growth and juvenile collection, and again highlighted the links between different highly specialised areas of research.

3.2 Model components development

At this stage, we have a representation of the system with its network of connections between the different components. In the next stage of the model building, we found a helpful sequential procedure:

1. first, express connection indicators in quantifiable variables.
2. then program each component *a minima* in order to model only the state variables required by the directly connected modules.

The formulation of each "actor" sub-model is determined by the indicators defining the connections to the other "actors". For example, in the Pertuis Charentais, the governance module needs water flow daily values at regulatory monitoring stations on the Charente river watershed (see Figure 1). The linked hydrology module must therefore be able to simulate these flows. In the same way, the socio-economic impact of the fresh water competition on shell fish farming is estimated through gains and losses of oyster sales due to lack of nutrient input from the river in coastal waters and subsequent loss of plankton productivity for oyster feeding. The oyster growth and production module is consequently designed to link phytoplankton input to graded oyster weight output (see Figure 3). Each sub-model is thus formulated *a minima* following the connection model network.
In terms of scales, time and space range from regional and yearly for economic information to less than hourly micro-level ecological processes [Westmacott, 2001]. For exploratory purpose, time and spatial scales must be detailed enough to be relevant to managers: monitoring networks must be simulated (flow values for the Charente River; micro-biological levels in oyster for the Thau Lagoon) and management areas must be represented (hydrological sub-catchments and counties, urban and industrial and areas). At the same time, the model must not become so complex that it looses its communication and learning qualities. For the two models, we chose a common daily time step which is appropriate for most ICZM processes. When necessary, it is possible to use a smaller time step e.g. an hourly step for the Primary Productivity module.

Environmental computer models, apart from multi-agent platforms, mostly deal with the physical or biological part of the system. A common bias observed in a number of SPICOSA study sites is for modellers to start building the integrated model from existing and often complex environmental models and then try to establish links to socio-economic modules. This often leads to a poorly integrated ESE model (Ecology-Social-Economy). Our experience on the two French study sites showed that it is crucial for integrated ESE modelling to approach the system with a top-down formulation from the socio-economics uses and governance components leading to the choice of the appropriate physical and biological resources models. Quoting Westmacott [2001] on ICZM modelling: "*There is little point in having a complex three-dimensional hydrological model when the economic model […] is a simple cause-effect relationship.*" The finality of the ESE model -in order to answer the questions asked by the stakeholders- constrains the necessary level of complexity for the physical and biological sub-models.

For the resources modules, complex models existed for some components in each study site previous to the SPICOSA experiment, e.g. SWAT model for agriculture [Arnold and Fohrer, 2005] or MARS-3D three-dimensional hydrodynamic model for the lagoon [Fiandrino et al., 2003]. Rizzoli et al. [2008] justly advocate reuse of existing tools. However, except for PC-Raster interactive raster GIS environment [Deursen and Wesseling, 1993], SPICOSA prescribed reformulating models in ExtendSim rather than developing coupling interfaces. Our experience showed that reformulating in a common software language and structure, which was at first felt as a constraining loss of time, highly improved communication and common understanding of the system in the end, particularly in a multidisciplinary experiment with scientists and modellers from different background and methods.

In an objective of flexibility and transparency, formulating *a minima* the sub-models requires thoughtful downscaling to target the necessary processes. In the Pertuis Charentais model (Figure 4), we translated in ExtendSim the parts the hydrological model used by the Water Agency managers needed to monitor the flow levels of the Charente river. However, in some cases, the system complexity bans downscaling e.g. the hydrodynamic transport in the Thau lagoon waters asks for a 3D model. However, the contribution of watershed outlet fluxes to micro-biological concentration at monitoring station in the lagoon are additive and allowed us to use transport transfer functions calculated off-line with MARS-3D.

For learning and communication purposes, ExtendSim software allows for a didactic modular and hierarchical organisation of the model. For the shell fish farm module a conceptual schematic presentation was used (Figure 3), with a block for each process: grow-out start, DEB (Dynamic Energy Budget) growth model, mortality, harvest, economical assessment, etc…. For the hydrology module, each sub-catchment is simulated by an identical reservoir model with specific data for each and time-lag connections between sub-catchments (Figure 4). Using a back-ground image over which to organise the different sub-catchments blocks conveys the spatial dimension of the system.

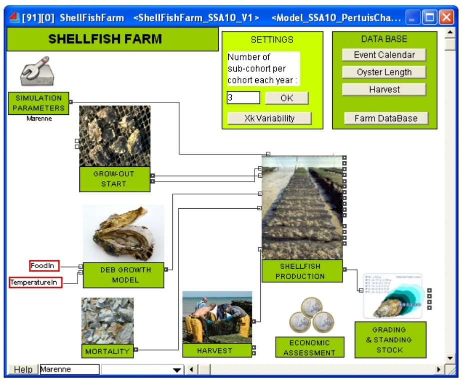

Figure 3. The Shell fish farm module

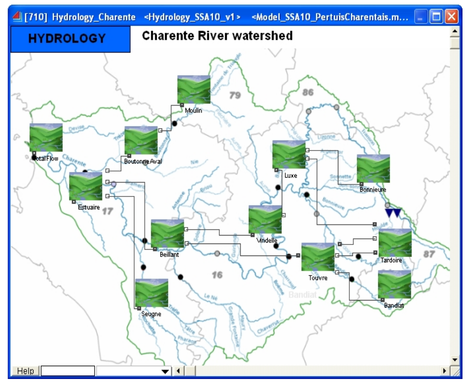

Figure 4. The Hydrology module

All the sub-models being at this stage formulated, appraisal is the following step in the DFA quality protocol. Considering the variety of processes to be modelled and the paucity of data, ICZM models are difficult to appraise and new assessment criteria must be established and used [Jakeman et al., 2006]. The models presented being highly modular, each component can be run separately with data in place of upstream connection and be validated against available data. This modular validation paired with sensitivity tests of each module leads to assessing if the chosen level of complexity is appropriate. For example, in the Pertuis Charentais model, the shell fish farming module (Figure 1) is forced by chlorophyll *a* and sea temperature calculated by the primary production module. A highly simplified Nitrate-Phytoplankton model was chosen for the production module which has been calibrated and validated on the Marennes-Oléron bay. Sensitivity tests on the shell fish farming block will determine if the coastal ecosystem representation is detailed enough or if other trophic compartments must be added.

3.3 Output construction

Classical scientific models deal with a high numerical production intended for an academic audience and are not necessarily adapted to decision support. Integrated socio-ecosystem models should not be designed for predictive or operational purposes. *A contrario* their outputs must highlight their exploratory, learning and communication aspects. The outputs must be carefully designed so as not to be misinterpreted and used out of context by end users. These tools should favour visual and animated indicators rather than classical graphs. The strong hypothesis taken in the *a minima* formulation step must be advertised an clearly documented.

Compared to physical sciences, models in biology, ecology and *a fortiori* in socio-economics require analysis of complex systems but lack data and process knowledge [Voinov et al., 2004 ; Voinov et al., 2008] leading to *““black-box” much of the underlying complexity*” [Voinov et al., 2004]. For exploratory models, formulation becomes a creative process [Jakeman, 2008] where uncertainty must not necessarily be avoided, but accepted and transparently advertised and documented [Brugnach et al., 2008]. Therefore, special care is given to documentation which can be called anywhere in the model in PDF format through "information" blocks (Figure 5).

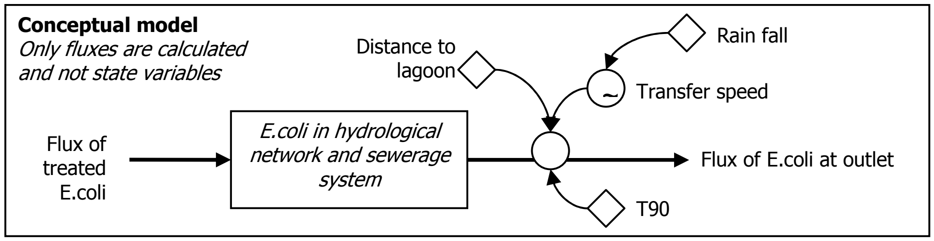

Figure 5. Example of model documentation (E.Coli transport on the watershed)

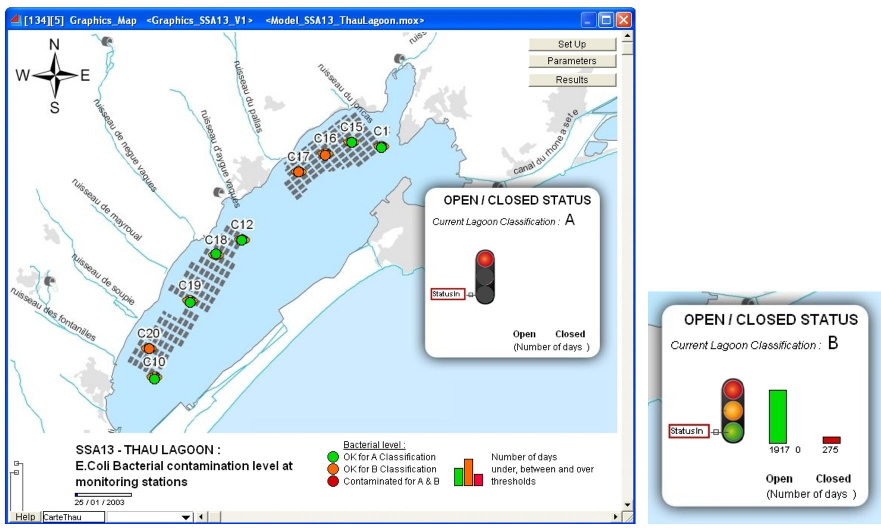

Figure 6. Animated visualisation of contamination level at monitoring stations. The traffic light visualises the open/closed status of the lagoon for shell fish commercialisation.

ExtendSim offers animation features that can be run during simulation, with a dynamic choice of speed. An animation tool was developed to visualise, over a chosen background image, any model variable with dots alternately coloured in green, orange or red depending of its value: under, between or over two selected thresholds. At the end of the simulation, histograms are plotted next to each dot visualising the number of days. This tool is used for the Thau lagoon to display the contamination level at monitoring stations. It is combined to a traffic light tool that visualises the "open/closed" sanitary status of the lagoon for shell fish farming commercialisation (Figure 6). This tool is used in the Pertuis Charentais model, to display the Charente river flow levels compared to regulatory thresholds at stations of the surveillance network. These tools were appreciated by stakeholders as well as by the scientific teams as they help to envision the dynamics of the system in a spatial representation.

4. CONCLUSION

The experience acquired while developing the models of the two French study sites, highlights the need of a detailed methodology in order to build successful integrated socio-ecosystem modelling platforms for deliberation support. Our approach covers a certain number of Westmacott's [2001] check-list for decision support tools: it incorporates multiple objectives and views, covers multi-disciplinary areas, deals with limited data and information, collates ICZM data and information and plays a learning role in the participant group. It also involves end users in the model development, offers an easy to use interface and visual displays of results.

At this stage of the project, we were pleased with the positive feedbacks from the participant group. The water management agency EPTB for the Charente river foresees a high potential for exploration of different management scenarios and is now highly involved in the continuing development of the model. They are also very interested by the communication possibilities of the tool for future discussions and negotiations with other management actors and local farmers. For the Thau lagoon, the water management agency (SMBT) representative was particularly interested in the potential for testing the numerous water treatment improvement options with an integrative outlook.

By the end of the SPICOSA project we will be able to offer detailed e-handbooks with the SAF integrated model building methodology as well as reusable ExtendSim block libraries from all the SPICOSA study sites with the ultimate objective of developing a virtual community of ICZM socio-ecosystem integrated assessment modellers.

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