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Abstract: The potential of Agent-Based Modeling is now well-established to address natural resource management and policy issues in social-ecological systems where a number of biophysical and anthropic processes interact. The selection of anthropic processes to be considered in a model according to the research question is not easy, due to modelers' difficulty to objectify and identify these processes. The paper proposes some criteria to identify anthropic processes, decide which ones to discard or retain and how to implement the latter. It is illustrated by the analysis of the governance sub-model of the MAELIA platform dedicated to the integrated assessment and simulation of water use and water management policy, in a context of land use / land cover and climate changes.

Keywords. Social-Ecological Systems, agent-based modeling, anthropogenic process, decision-making process, purposive / generative model, macro / meso / micro processes, functional explanation.

1 INTRODUCTION

Environmental and natural resource management issues involve multiple interactions between ecological processes and many actors having diverse and contrasting interests and objectives (Reed, 2008; Pahl-Wostl, 2007). Biophysical and anthropic processes act concurrently, directly or indirectly, at their respective scales of time, space and magnitude, on natural resources' states and dynamics. They occur in *social-ecological systems* (SESs) in which interactions within and between social and ecological subsystems give rise to emergent phenomena at sub- and whole-system levels (Ostrom, 2009). *Integrated Assessment and Modeling* is an approach that consists in assembling particular models of system components into an integrated modeling platform (Parker et al., 2002). A model expresses a representation that observers build based on the knowledge that they pool about a *system of reference* (SR), e.g. a SES. Model-based methods collect data and knowledge from a wide range of scientific disciplines and integrate them to investigate a *research question*, to analyze system responses to changes and to design sustainable management strategies, often in a policy oriented context (Tol & Vellinga, 1998). An *Agent-Based Model* (ABM) is composed of elements in relation that correspond to well-defined entities of the SR under study, so that the model's organization mirrors the modelers' representation of the SR. It also describes interdependent dynamics of these elements and thus allows to simulate the SR functioning. ABMs have proved particularly well suited for representing anthropic processes and the interactions, in space and time, between actors and with their normative and natural environments (Bousquet & Lepage, 2004; Parker et al., 2002).

In *coupled natural and human systems* (Liu et al., 2007), the biophysical processes that are likely to contribute to the occurrence of the phenomena of interest, and thus must be considered in the model, are known in advance: they depend mainly on the nature of the phenomena and weakly on the SR peculiarities. Things are much more complex regarding anthropic processes: the social sub-system includes a bundle of decision-making processes that serve specific purposes and interests of actors and contribute in various ways to the whole system dynamics. In other words, anthropic processes are contingent on the specificities of involved individuals and on the social context where they take place (An, 2012; Shepherd & Maynard, 2014). As the processes at play are proper to the SR, their identification and understanding require specific investigations and analysis. Accordingly, modelers

have to untangle processes and delineate each one to decide (1) which processes to take into account and (2) how to describe and integrate them into the model.
The purpose of this article is to investigate these issues, illustrated by the governance subsystem of the Integrated Assement and Modelling MAELIA platform (Mazzega *et al.,* 2014). In Section 2 we first introduce the MAELIA platform, with brief overviews of the French water management normative frame and of the model architecture. Relying on this case, in Section 3 we introduce a distinction between purposive and generative models of anthropic processes, we present heuristic criteria for identifying anthropic processes to be considered in SES simulation models and for designing corresponding models. Our conclusion is drawn in Section 4.

2 MAELIA AND THE QUANTITATIVE MANAGEMENT OF WATER RESOURCES

The MAELIA project has developed an agent-based simulation platform for the joint assessment of environmental, economic and social impacts of various scenarios of water use and water management policy in combination with land use / land cover changes and climate change. This platform is intended to assess management policies and to support decision-making processes of organizations involved in water scarcity management. While the expansion of drought periods leads to an increasing demand for irrigation, these organizations are required to accommodate to the new regulatory framework of the agricultural use of water resources resulting from the French implementation of the European *Water Framework Directive* (WFD 2000/60/EC). MAELIA's modeling architecture and components, scenario construction and application examples (especially in the Adour-Garonne basin - southwestern France, which regularly suffers severe drought problems) are described in Gaudou et al. (2014) and Therond et al. (2014). A complete documentation is given at http://maelia-platform.inra.fr. To address the anthropic processes of the water resource management subsystem of MAELIA, we first need to look at the regulatory frame.

2.1 Regulatory Frame of Quantitative Water Resource Management

The French water regulatory system is a complex hierarchical construct that extends from the European level (which defines long term general principles and objectives common to the 28 States of the European Union), to the National level (which defines the means and duties of institutional actors), the River Basin level (where the Basin Committee determines objectives to be reached, overall orientations regarding water management and means to bring into use), and the elementary watershed level where operations take place and concrete issues occur.
The management policy of a watershed is specified by its "Low-water management plan" that aims at ensuring a long-term satisfying coexistence of all human water uses (drinking water, industry, energy, agriculture, transportation, fishing, tourism and sport) along with the sustainable functioning of aquatic ecosystems (Mayor *et al*. 2012). Most measures concern agriculture, which withdraws 50% and consumes up to 80% of the water volume in low-water periods, while the expansion of drought periods leads to an increasing demand for irrigation. The MAELIA model is a fine-grained model at the scale of crop field. It considers the concrete implementation of policy tools for the preservation of healthy aquatic ecosystems and the management of agricultural abstraction volumes, their allocation and the control of actual agricultural withdrawals.

2.2 Architecture of the MAELIA Model

In line with the "Overview, Design, Details" documentation protocol (Grimm *et al.*, 2010), the model of a SES consists of a set of related entities (its structure) weaved with a set of processes (its dynamics) (Sibertin-Blanc *et al.*, 2011; 2016). The *structure* of a system is composed of *entities* and *relationships* between them. According to conceptual modeling, entities are characterized by attributes and endowed with operations that process attribute values. Three categories of entities are distinguished in MAELIA:

- an ***Actor*** *is* a human agent that performs some activities, be it an individual, a population of similar individuals or a collective (e.g. organization, association, etc.);
- a ***Material resource*** is a physical object, spatially and temporally distributed (e.g., a water body, a field plot, a dam), involved or taking part in the system functioning;

- a ***Cognitive resource*** is an information, believe, expectation, aim or procedural knowledge that actors use or consider in the activities they undertake, in the formation of goals or in decision-making processes (e.g. weather forecast, cropping plan, expected harvest).

The *dynamics* of the system is the set of processes that generate the phenomena of interest (e.g. river flow). Processes handle entities, and thus make the state and possibly the structure of the system evolve. Three categories of processes are distinguished:

- an ***Ecological process*** is the natural action of biophysical laws that conduct the evolution of some material resources (e.g. run-off of water, growing of crop, aging);
- an ***Activity*** is an action executed by a well-identified actor entity who intends to achieve some goals and involving from some kind of decision-making process (e.g. irrigate a field plot, release water from a dam, issue a Drought decree);
- a ***Socio-economic process*** is the global result from a set of human economic or social actions which are not ascribed to particular actors (e.g. changes in land cover and use, evolution of market prices).

According to this classification, anthropic processes are the activities performed by actors and the socio-economic processes. Interactions between processes take place through their common use of entities of the system structure: at each time-step of a simulation run, the current state of entities determines the processes that are enabled and the processing they have to perform; at the next time-step, processes will consider the entities state resulting from the performance of these processing. In other words, entities are the medium that supports interactions between processes.

Thanks to this modular model architecture, processes are described independently of each other once their interface entities are determined. Integrating a process into the model 'just' requires answering the following questions:

1. is it an ecological process, an activity performed by a given actor or a socio-economic process?
2. what are the temporal, and possibly spatial, resolution of the process?
3. what are the entity attributes whose value is changed by the process executions?
4. whether it is an *external* (exogenous) or an *internal* (endogenous) process
5. in case of an external process, what is the data time series to be used as a *forcing input file* during simulations?
6. In case of an internal process, what is the dynamics of the process and the entities properties that determine its regime?

The MAELIA platform includes a number of ecological processes related to hydrological (using the SWAT "Soil and Water Assessment Tool" model; Neitsch *et al.*, 2009) and crop growth dynamics as well as socio-economic processes dealing with demography, land cover / land use changes or domestic and industrial water uses (Gaudou *et al.*, 2014). The model of farmers' activities such as cropping plan decision-making and crop management is presented in (Taillandier *et al.,* 2012).

3 MODELING AND CONSIDERATION OF ANTHROPIC PROCESSES

We now introduce a distinction between two types of models of anthropic processes, and propose criteria to identify which processes to consider in a SES simulation model and how to model these processes, with a focus on decision-making processes.

3.1 *Generative* vs *Purposive* Model of Anthropic Processes

Regarding ecological processes, it is common to distinguish a *mechanistic* model, which relies on deep knowledge and replicates the biophysical mechanisms that produce the process's effects, from an *empirical* model that just provides the observed process's effects without considering how they are really produced (Estes *et al.,* 2013). Regarding anthropic processes, it is relevant to introduce a similar distinction between *generative* and *purposive* models of a process.

We assume that, in models of social-ecological systems, humans' activities are rational as they are guided by the achievement of some aims according to the actor's believes. A *purposive model* of an anthropic process focuses on the fulfillment of the goal aimed by its performances without worrying about the cognitive means enacted to achieve the goal. The effect on entities impacted by its performances is derived in an analytic way from the (state of) input entities by means of "if-then-else" rules, conditional formulas, equations, more generally an algorithm that is applied at each occurrence of the process. As an example, MAELIA farmers decide the scheduling of agricultural operations (e.g. tillage, irrigation) to perform in applying a set of "if-then-else" rules that consider unfinished eve tasks, priority and duration of next tasks, current weather and distance between fields to be worked. The model of a socio-economic process is by definition purposive since it is viewed as the global result of a number of actions and interactions whose details are disregarded.

Another example of purposive model in MAELIA is the enactment by the prefectural authority of a Drought decree that states water withdrawal limitations (some days in a week) or total prohibition in some place for some duration and usage. While the decision to issue a withdrawal restriction is often the conclusion of a laborious collective decision-making process (see below 3.3), outcomes of this process can be described as the output of a decision tree that considers: the actual flow rates at monitoring points in comparison with regulatory thresholds; the trend of weather forecasts; the current and upcoming agricultural water needs; the possibilities to release water from volume yearly contracted to face water shortages in upstream dam; the application of the upstream-downstream solidarity and continuance principles; the likeliness of farmers' non-compliance with the restriction depending on the frailness of crops.

A *generative model* of an anthropic process considers how human beings proceed, or could proceed to produce outcomes and it implements this way of achieving the aims of this process. The design of a generative model requires having a socio-cognitive theory of the mechanisms enabling to generate the process outcomes. A typical cognitive model is the Expected Utility Theory: to select one option among a set of given alternatives, each alternative is assessed through a predefined utility function and the one with the highest score – adjudged the best one – is chosen. The MAELIA farmers' annual cropping plan decision-making process presented in Taillandier et al. (2012) is an example of such utility-based generative model. It is a Beliefs - Desires - Intentions model based on the Dempster-Schaeffer theory for decision-making that allows to manage information incompleteness, uncertainty and imprecision. The farmers' desires are the following optimization criteria: (a) maximize profit; (b) minimize the variability of income; (c) minimize workload; (d) minimize the changes from the choice of previous years. The utility function associated to each criterion captures the empirical knowledge of farmers on the functioning and on the response of agricultural systems (including uncertainties). Each farmer chooses a cropping plan of crop rotations within a set of predefined plans, according to the specific characteristics of his farm (including environmental and regulation contexts).

Besides the Rational Choice Theory, there are many other socio-cognitive paradigms such as case-based reasoning (Aamodt et Plaza, 1994), learning (Busoniu *et al.*, 2008), bounded (Shuster, 2012) or procedural (Selten, 1998) rationality. Balke and Gilbert (2014) compare and analyses the suitability of 14 decision making computational models. Regarding generative models of collective decision making processes involving many participants such as the enactment of a Drought decree, a number of models have been proposed that study how a consensus can emerge among a society of agents (see for example the JASSS journal).

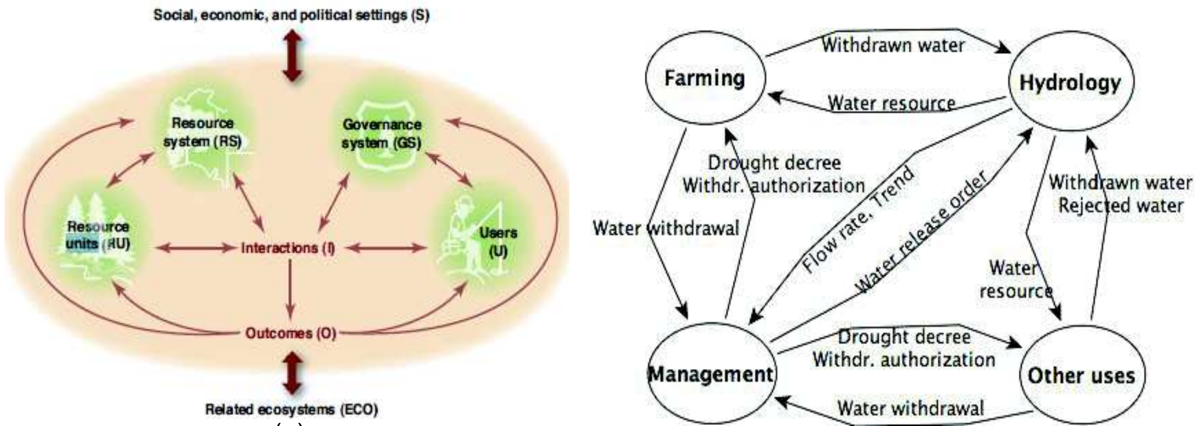
Designing a purposive model requires to notice, in the SR, a systematic correspondence between, on the one hand the process's effect on impacted entities and, on the other hand the state of entities that determine this effect. The implementation, as well as the validation, of a purposive model generally raises less difficulty so that it is preferred to generative model. A generative model is necessary when there is no available evidence for a purposive model. Its design, implementation and validation are more demanding, and it has a higher computational cost. A generative model will be chosen also to test the founding theory against data, or when the purpose of the model is to provide explanations about its working rather than to reproduce the phenomena observed in the SR or to provide predictions about its future (Elsenbroich, 2012; Epstein, 2006).

3.2 Scale of Anthropic Processes

A first criterion for untangling anthropic processes is to consider their scope, in regard to the model's research question, at the micro, meso or macro level. A *macro process* is a wide scope process which occurs once in particular circumstances. It has a long-term and deep effect on the system as it changes the social structure and the normative framework that regulates its dynamics. It is somehow a meta-process that acts on the SR's structure by introducing new entities or entity attributes, changing the goals and activities of actors or the dynamics of socio-economic processes. It thus strongly transforms the functioning of the system. Examples of macro processes are the shift, in France, from the management of water scarcity by flow (water abstraction is restricted when flows are too low) to management by volume (yearly water abstraction volumes are fixed in advance; Mayor *et al.,* 2012), or a severe and long-lasting social conflict with open-ended consequences such as the strong adaptation of the reform of water management reported in Mazzega *et al.* (2014: 4.2)[1]. As for the outcomes of a macro process, either it may be known in advance and its issuing is just a matter of time, because its course is guided by the application of firm principles that progressively prevail and raise weak opposition, or it may be definitely unpredictable, due to the number and indetermination of elements that might deviate the process and determine the final decision. Anthropic macro processes are not integrated into models because this would require endowing the model with the capacity to evolve its own structure by the introduction of or changes in types of entities or relationships, in correspondence with the consideration of new processes or significant changes in the logic of current processes. Moreover, the achievement date of macro processes is generally very uncertain (Mazzega *et al.*, 2014). Thus, safe consideration of a macro process consists in designing scenarios that integrate the new system structure (Leenhardt *et al.,* 2012).

Micro processes are those determining the regular and short term functioning of the SR. They occur systematically at a fixed temporal resolution all along the duration of simulations. Such a process needs to be included into the model, to the extent of its contribution, in intensity or variability, to the phenomena of interest. For instance, the MAELIA farming module includes the farmers' annual choice of crop rotation and their daily decision about the scheduling of technical operations: tillage of various intensity and depth, sowing, irrigation, harvesting, fertilization and plant protection.

In-between, meso processes are middle-term processes, which have a significant effect on the SR's behavior but do not drastically disrupt its course. Typical meso processes produce changes in the value of parameters – e.g. the amount of water-use taxes, the volume of water contracted for water releases, or flow reference thresholds at some monitoring points. They may introduce new entities instances – e.g. new monitoring points or dams – but not new types of entities. The completion time of a meso process is likely shorter than the simulation duration, so that it can occur several times during a time-period covered by simulation. The occurrence and outcomes of a meso process most often depend on factors beyond the control of the system so that its consideration gives rise to an external process of the model. Therefore different hypotheses about outcomes of a meso process will be tested by scenarios which differ with respect to forcing input files. The MAELIA platform deals with the Land Cover Change meso process in this way, based on statistics derived from past Corine Land Cover observations.



(a) (b)

Figure 1. (a) Core subsystems of the framework for analyzing SES systems (Ostrom, 2009)
(b) The subsystems of the MAELIA model connected by resources supporting interactions.

3.3 Systemic Viewpoint and the Simon's Functional Explanation principle

According to the Ostrom's framework for analyzing SESs (Ostrom, 2009), a SES model is decomposed into interacting core subsystems. According to the MAELIA architecture, these interactions occur through the exchange of resources as shown in Figure 1. This systemic view points out that essential processes are those impacting resources shared by subsystems and hence influence the system as a whole. Thus, the main processes of the MAELIA Management subsystem are Drought decrees enactment and water release ordering (we explain below in 3.4 why the Water

[1] In the Adour-Garonne basin, this conflict led to authorize water abstraction volumes that fulfill all demands and are untenable, and thus will be called into question by a forthcoming meso or macro process.

withdrawal and Withdrawal authorization processes to and from the Management subsystem may be disregarded).

Processes that support subsystem interactions are likely to be considered by a purposive model in application of the Simon's *Functional Explanation* principle (Simon, 1996): the outputs of a (sub)system can often be predicted from knowledge of its main goals and of its environment, with only minimal assumptions on its internal organization (Simon, 1996), because the environment imposes constraints on the ways to achieve goals and the actors' rationality leads them to satisfy these constraints to survive. For the water management and regulation subsystem, constraints bear on the acceptability by farmers and other users of water withdrawal restrictions and on the sustainability of the hydrological system, and the outcomes of the subsystem is merely a local compromise between these constraints. The Simon's Functional Explanation principle works in this case because, despite the variety of actors involved in water management and regulation, no severe conflict among them deviates the subsystem from the achievement of its function (that defines its goals).
Low-water management involves many actors which contribute in various ways to the regulation of water availability and use, each one with specific duties and means. However, the purposive model of the Drought decree enactment and water release ordering processes allows MAELIA to consider only the Prefect and the basin manager actors and exempts from considering the specific contribution of other actors. Notably, though the Drought committee is an essential piece of low-water management, it is not considered in the model. The Drought committee is an advisory committee to the Prefect where State services present to representative of stakeholders the Drought decree(s) they envision for the week(s) to come. It is a participatory arena allowing to exchange information and perceptions or feelings, and to discuss wishes and possibilities as expressed by a diversity of involved actors. This committee appears to serve primarily to prevent conflicts by building a shared representation of the hydrological and agricultural situation in a collective learning and negotiation process (Kørnøv & Thissen, 2010). While the Drought committee plays an role essential for the regulation of emotional states of people and the quality of social relationships within the system, this actor does not appear in the model because, regarding water availability, the outcomes of its meetings is mostly known in advance and summarized in the purposive model.

3.4 Processes to Discard

There is a number of activities contributing to low-water management and being essential to its processing that do not appear explicitly in the list of MAELIA's processes, because they have no effect on the state of impacted entities or because the effect can be automatically enforced.
Some processes are just the formal application of compulsory norms or the perpetuation of old habits which are actually not effective in that they do not impact the course of other processes. The application for and grant of withdrawal authorization fall in this case: because the State services do not have the capability to assess whether the total amount of water volumes asked for abstraction is compliant with the capacity of water bodies, they grant the quantity requested by each applicant year after year. Thus, all water demands are satisfied and farmers are not constrained by the granted quantities because each one requests the maximum quantity it has withdrawn in previous years. So, the MAELIA model includes no element regarding water withdrawal authorizations: it does not include activities "apply", "grant" and "declare" regarding water withdrawal volume and the Farm actor does not have a "granted withdrawal water volume" attribute.
On the other hand, there are processes that are performed in a systematic way and raise no doubt about the effectiveness of their expected achievement such as the purchase of prescribed volumes for water release by local authorities or the execution of release orders by reservoir operators. For this kind of activities, the outcome is certain – they include no choice since they are just the implementation of well-specified regulatory tasks or the application of decisions made by other activities – and their performance faces no difficulty. They are routine processes and we may assume they are achieved as specified in any case. Accordingly, the model takes for guaranteed that water volumes planned to support water shortages are bought in due time (this volume is a constant attribute of each water reservoir), that reservoir operators scrupulously apply release orders (calculations of flow rates assume that decided release orders are done).

3.5 Processes of Information Acquisition and Diffusion

The processes that deal with the acquisition and diffusion of information have very different forms in the SR (the "real world") and in the model's numeric world. Information acquisition concerns data that are used in decision-making processes such as, for example, knowledge regarding weather forecasts, soil moisture of fields, phenological state of crops or current flow rate at monitoring points. In the SR, obtaining these data may be dubious and costly, e.g. some monitoring points are not equipped with measuring device and the management and carrying out of measurement tours is a heavy workload. On the other side, in the model actors have straight access to all variables characterizing the system's state, so that specific processes dedicated to acquire data are useless. Just time and effort devoted to these tasks may be counted in the model, if relevant. Moreover, to consider flaws in a data acquisition process, the model can filter accesses to alter some qualities of a data such as: a) timeliness: a previous value is used; b) precision: an approximate value is used; c) accuracy: the value is chosen at random inside an interval (more or less wide and symmetric) around the value, with a probability law yielding, e.g., a uniform, biased or Gaussian distribution of the used values (this filtering can include cases where a constant or random value is used); d) privacy: (un)authorized access, (un)accessibility and so on.

The filter can be applied at each access to the data, or actors can store the value, once it is acquired, as a cognitive resource of its own. The same filter can be used for all accesses, or it may be tailored according to some actors' properties. The case where an actor does not know the existence of given information he could use, and that other actors use can also be considered. The lack of filtering access to state variables of a model sometimes leads to simulation results featuring peaks that do occur in the SR: if all farmers had the same assessment of the phenological state of a crop, they would all harvest the same day. Information diffusion processes face the same failings, with a strengthening of timeliness issues since the information can fail to reach some actors. In the MAELIA platform, all actors have access to Drought decrees as soon as they are enacted.

4 CONCLUSION

Environmental sciences are much more familiar with the modeling of natural processes than with the modeling of human and social activities. For instance, the growth of plant is a well-defined process that falls in the range of disciplines offering strong theories, tools, methods, etc., and modelers may choose what they need in this well-arranged panoply or complete it. Regarding anthropic processes within coupled natural and human systems, each case features idiosyncrasies. This hampers an agreement on a ready-to-use classification of processes. Even setting the list of all activities that somehow contribute to the phenomena of interest is far from a trivial work. Plenty models of social processes are available but they lack the generic character required for an easy and wide use.

However, social sciences include some well-established results and principles that can guide the design of the human dimensions of SES models. As a contribution to the SES modelers' toolbox for drawing a picture of the anthropic processes to consider in SES modeling, this paper proposes heuristic criteria to identify and characterize anthropic processes and suggest how they may be dealt with. In particular, it draws a line between the purposive models who stick to reproduce the phenomenological results of anthropogenic processes without representing the underlying mechanisms, and generative models which place at the center of simulations a representation of involved mechanisms - especially decisional processes - leading to an observed evolution of the system or of one of its components.

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