Multiagent Modeling and Simulation of Hydraulic Management of the Camargue

Bernard Espinasse  
Nathalie Franchesquin  
LSIS (UMR CNRS 6168)  
Université d'Aix-Marseille  
Domaine universitaire de Saint Jérôme, 13397  
Marseille, Cedex 13, France  
bernard.espinasse@univ.u-3mrs.fr

Modeling and simulation of human-influenced ecosystems require the integration of natural and decision-making processes. In such ecosystems, natural resource management aims at protecting natural areas while enabling human activities that contribute to these area characteristics. The object of this research is the modeling and simulation of the hydraulic management of the Camargue ecosystem with a multiagent system. The authors first present the problematics of this hydraulic management, its objectives, and a formalization of the different decision processes centered on a social contract and associated with two main phases: the contract elaboration phase and the contract realization phase. They present conceptual modeling and multiagent modeling of these two phases with details on agent models, agent behaviors, and negotiation models.

Keywords: Multiagent system, modeling, simulation, negotiation, human-influenced ecosystem, hydraulic management, Camargue

1. Introduction

In human-influenced ecosystems, natural resource management aims at protecting natural areas while enabling human activities that contribute to these area characteristics. Consequently, ecological and social dynamics interact, and it is necessary to integrate natural processes and decision making to model and simulate such ecosystems.

Agent-based models enable one to represent entities, their behavior, their interactions, and their environment [1]. The system's global behavior is the consequence of a set of interactions between agents. Examples of such works are the multiagent simulation of fishermen on the Niger inland delta [2], the simulation of walkers' behavior in a natural environment [3], the agent-based simulation of catchment water management in northern Thailand [4], and a multiagent model to negotiate water demand management on a free-access water table [5]. Such agents that are able to communicate and deliberate allow us to model decision processes, actor reasoning, and cooperation and are therefore suitable to model human-influenced ecosystems.

The Camargue is a strongly human-influenced ecosystem located in the south of France at the mouth of the Rhône River. A study about the future of this human-influenced ecosystem is currently under development on a national and regional level. The hydraulic management of the Camargue is the main characteristic of this human influence. This research deals with the modeling and simulation of this hydraulic management with a multiagent approach. The aim of this research is to contribute to this study, first to better understand the dynamics of this strongly human-influenced system and then to provide a simulation tool permitting the investigation of various scenarios about the evolution of this ecosystem. This simulation tool has to be the starting point for the development of an EDSS (Environment Decision Support System) to define future investments and management rules related to this ecosystem.

The Camargue is the subject of many studies, particularly hydrologic studies [6], which concern only one catchment basin and use analytic simulation models. Until now, none of these studies has concerned the hydrologic system in its totality, and none has attempted to make the link between hydraulic management decisions and the state of this ecosystem.

This article is organized as follows: section 2 is devoted to the problematic and the objectives of the hydraulic management of the Camargue ecosystem. Section 3 presents a conceptual modeling of specific decision processes associated with this hydraulic management. Section 4 describes the multiagent modeling of these two phases, with details
on agent models and agent behaviors, as well as negotiation processes and models. Section 5 is devoted to the multiagent system prototype that we have developed. Section 6 presents the validation and simulation results obtained with our prototype and their interpretations. Finally, we conclude by introducing some perspectives to this research.

2. Hydraulic Management in the Camargue Ecosystem

Located in the Rhône delta, the Camargue is an alluvial plain exposed to the influences of a salty water table and a Mediterranean climate. The Camargue ecosystem depends greatly on human activities [7]. These activities require massive introduction of freshwater that compensates for the hydric deficit and washes soils of their salt, allowing the development of activities such as agriculture, salterns, tourism, hunting, and nature conservation.

To allow the development of activities such as agriculture, an important network of irrigation and drainage canals has been built. Hydraulic associations (Fig. 1) are associated with a specific catchment basin and manage these canals, each of them providing irrigation or drainage services for the farms situated on their area [6, 8]. The range and intensity of anthropogenic influences within this catchment basin mainly depend on the hydraulic management.

More precisely, we study the hydraulic management of the “Grande Camargue,” a land located between the arms of the Rhône River. This area is famous all over the world for its halophilic fauna and flora.

From a hydrological point of view, this delta behaves as the catchment basin of the central lagoons system. The water flows from the Rhône River to a lagoons system named the “Vaccarès system.” Due to the important inputs of freshwater for agriculture, a part of this delta has been polderized ["PLS. DEFINE “POLDERIZED”"]. Drainage associations currently do the management of drainage waters. These associations drain water surpluses coming from the farms to the Rhône River or to the Vaccarès system.

People who participate directly in this hydraulic management are (1) the farmers in charge of the management of agricultural parcels and hunting marshes; (2) hydraulic associations, which are in charge of draining the land situated on their area; and (3) the PNRC (Parc Naturel Régional de Camargue [Camargue Natural Regional Park]) administrator of the sea dike.

As shown in Figure 2, this management modifies the water level and the water salinity of the Vaccarès system, a set of lagoons belonging to the National Reserve. For example, the choices of crops and cropping techniques by farmers modify the quantities of water to be drained. The level and salinity of this system are essential for the ecological quality of the entire area.

The drainage associations have to manage a large amount of drainage water by defining in particular the proportion of water that will be pumped back to the Rhône River and, consequently, water that will be poured by gravity into the Vaccarès system. The management of the sea dike deals with exchanges between the Vaccarès system and the Mediterranean Sea.

3. Conceptual Modeling

Our formalization of the decision processes, which influence the hydraulic management of the delta, is based on two phases of the life cycle of a contract:

• The elaboration of a contract is a phase in which collective objectives relating to the ecosystem are defined. The general purpose of this phase, which takes place during the CDE (Water Council), is to determine the water level and the level of salinity of the Vaccarès system that partners want to reach. This contract is negotiated between the representatives of the fishing, agricultural, and nature conservation activities, and it has to be respected by the members of the collective hydraulic management: the hydraulic associations and the manager of the sea dike.

• The realization phase of the contract describes the negotiation between these partners in order to define an action plan, which will allow this contract to be respected. The action plan states the water quantities to be drained from the Vaccarès system by each association and the opening modes of the sea dike.

3.1 Contract Elaboration Phase: Negotiation Model for the CDE

The elaboration of a contract is a crucial phase in which collective objectives concerning the ecosystem are defined. The object of the negotiation process associated with this phase is to elaborate a contract, which defines for each
period of the year the level and the salinity needed for the Vaccarès system. We represent this process as a negotiation of a contract between partners with a mediator. The different participants are the mediator, which is the Camargue Natural Regional Park (PNRC) representative, and the parties, which are the representatives of human activities (fishing, agriculture, and nature conservation).

The negotiation issues are the water level and water salinity of the Vaccarès system. It is a cooperative and multilateral negotiation with proposals for various attributes.

3.2 Modeling the Contract Realization Phase

The realization phase of the contract describes the negotiation between these partners in order to define an action plan, which will permit this contract to be respected. The action plan defines the water quantities to be drained from the Vaccarès by each of the associations and the opening modes of the sea dike.

3.2.1 Negotiation Process Overview

The obligations of the contract issued in the elaboration phase (water level and salinity of the Vaccarès system) are given for each month of the year. To respect these levels, the sea dike manager and drainage associations negotiate for defining an action plan, which takes changeable climatic conditions into consideration.

The contract realization phase is based on four steps (Fig. 3) for each month of the year:

- **Step 1**: Inputs and outputs of water upon plots lead to an amount of water to drain.
- **Step 2**: Each drainage association gathers this amount of water from the plots it drains and then defines the amount it wishes to drain toward the Vaccarès.
- **Step 3**: The manager of the sea dike updates his or her information about the states of the Vaccarès system and the sea and starts the negotiation to define an action plan in order to respect the contract. This plan defines the amount of drainage water to be drained toward the Vaccarès system by the association and the opening modes of the sea dike.
- **Step 4**: The plan is applied, and this phase ends.

3.2.2 Negotiation Model

The purpose of the negotiation process associated with the contract realization phase is to elaborate an action plan that permits, depending on climatic conditions, fulfilling the contract terms defined in the elaboration phase. The participants are the sea dike manager and the six drainage associations. The negotiation issues are as follows:

- the amount of drainage water to be drained toward the Vaccarès system by each drainage association (these associations are able to help each other),
- the opening modes of the sea dike (how many gates are to be opened for what amount of time), which allow exchanges between the Vaccarès system and the Mediterranean Sea.

We model this negotiation as a bilateral process between the sea dike manager and the drainage associations. In this negotiation, the participants are cooperative and try to fulfill the contract.

The negotiation process follows these steps (Fig. 4):

- **Step 1**: The sea dike manager asks from each drainage association the amount of water it wishes to drain toward the Vaccarès.
- **Step 2**: Each drainage association makes a proposal according to the total amount of water it has to drain (which depends on land occupancy in its area).
- **Step 3**: The sea dike manager evaluates these proposals, according to the exchanges allowed between the sea and the lagoons, if the fulfillment of the contract is possible.
4. Multiagent Modeling

According to the conceptual modeling presented in the previous section, we present now our multiagent modeling of the hydraulic management. First, we introduce our modeling framework based on two complementary and coupled models. Then we present the chosen multiagent architecture and agent, negotiation, and decision models. Finally, we detail interaction protocols adopted for each of the two main phases related to this hydraulic management: the contract elaboration phase and the contract realization phase.

4.1 Modeling Framework

To describe this ecosystem and its hydraulic management, we have defined two complementary models: the first one is a hydrologic model reflecting the subsurface water fluxes, while the other, the social model, represents decision processes in water management [9-11].

4.1.1 Hydrologic Model

The hydrologic model establishes the environment model of the social model modeled by a multiagent system. This model is an object model, which describes the ecosystem’s entities on which agents are going to intervene: the plots, the canals, and the sea dike. The main classes making up the model are presented in the class diagram of Figure 5.

The cell grid (from GIS Camargue) that partitions the entire study area is based on the drainage area, farm area, land use, and altitude. Each spatial unit, a plot in the hydrologic model, is a square cell of 100 meters (equivalent to the average size of a rice field) and is supposed to have a homogeneous behavior when exposed to water fluxes. The hydrologic model’s dynamics is based on a simplified water cycle. Each month, it iterates the following

- **Step 4**: If it is possible, sea dike manager works out the opening mode of the sea dike, and the drainage association proposals are agreed on. These proposals and the opening mode of the sea dike define the action plan, which permits fulfilling the contract.
- **Step 5**: Otherwise, the sea dike manager calls for a new proposal and tells the drainage association how to modify their proposal (to increase or decrease the amount of water to be drained toward the Vaccarès).
- **Step 6**: If the drainage associations have to increase their proposal, they are able to propose a higher amount if it is less than or equal to the total amount of water they have to drain.
- **Step 7**: If drainage associations have to decrease their proposal, they are limited by their pumping capacity, and if it is not enough, they can ask help for drainage from other drainage associations.
- **Step 8**: This process iterates in 2.

It ends when an action plan is found or when there is no solution, so the solution that is not as bad is chosen by the sea dike manager. In this negotiation, several strategies have been defined for the drainage associations, depending on their polderization.
Figure 5. Hydrologic model: class diagram

steps: rainfall, evaporation, irrigation, gathering of requests for drainage, realization of the drainage, and calculation of the exchanges with the sea. This cycle depends on the decisions made by the agents of the social model.

The sequence diagram of Figure 6 illustrates these dynamics in specifying, for each plot and each month, how the climatic conditions are taken into account, and the new state of the ecosystem and the quantity of water to drain for each catchment basin are calculated.

The sequence diagram of Figure 7 illustrates how management decisions are taken into account about the social model agents in regards to the quantity of water to drain in the Vaccarès and the modalities of dike opening.

4.1.2 Social Model

The social model is a multiagent model whose agents represent the behavior of partners of the hydraulic management. These agents make management decisions about the resources they have and are described in the hydrological model. To elaborate this model, we were inspired by the AOM method proposed by Kinny and Georgeff [12].

We identified different types of agents: PnrcAg, DikeManagAg, ActivityAg, AssoDrainAg, AssoIrrigAg, ExploitationAg, and HydroAg.

• The PnrcAg agent is associated with the PNRC (Camargue Natural Regional Park) and is taken as a decision-making entity. There is one instance of this type of agent in the system.
• There are three ActivityAg agent instances: AgricultureAg, FishingAg, NaturConsAg, which are representatives of human activities (fishing, agriculture, and nature conservation).
• AssoDrainAg, AssoIrrigAg, and ExploitationAg agents are respectively associated with the drainage associations, the irrigation associations, and the farm exploitations. Their number in the system is the number of drainage basins, the number of irrigation basins, and the number of exploitations, respectively.
• The HydroAg agent realizes the coupling between the hydrologic model and the social model. This agent initializes all hydrological model objects, then governs the water cycle according to the management decisions taken in the social model. This agent transmits the calculated hydrological states to the DikeManagAg and the AssoDrainAg agents and takes orders from them.

Figure 8 presents an agent diagram that shows the agents and their relations. Note that the AssoIrrigAg, associated with the irrigation association, is not take into account in our modeling because these associations are not present in our decision processes.

This formalization of the agent diagram is based on the UML notation for class diagrams. The diagram box represents types of agents or agent classes. This agent model
notation, proposed in the AOM methodology, is extended [13] to take into account relations between agents.

There are two sorts of relations between agents: (1) inheritance relations, represented by arrows going from the child class toward the parent class, and (2) relations (lines connecting two agent classes), which indicate interactions between these agent classes.

For example, the relation WaterCouncil between the PnrcAg and ActivityAg agents corresponds to a conversation between these agents for the contract elaboration phase. In this conversation, the PnrcAg holds the mediating role, whereas ActivityAg holds the activity role. In the diagram, these roles are indicated next to the agent.

4.2 Multiagent System Architecture

Figure 9 presents the general architecture of the multiagent system, associated with the social model, with its various agent components and its interaction with hydrologic model classes that is assumed by the HydroAg agent.
4.3 Interactions and Agent Models for the Contract Elaboration Phase

The aim of this phase is to elaborate a contract by negotiation between the various partners of the hydraulic management, which are the representatives of each activity (fishing, agriculture, and nature conservation). This negotiation process involves the activity agents (FishingAg, AgricultureAg, NaturConsAg) and the PnrcAg as the mediator agent.

4.3.1 Negotiation Process Overview

The interaction protocol between agents adopted in this negotiation process is an extension of the Contract Net Protocol (CNP) proposed by Davis and Smith [14]. This protocol, named CommissionEau, is presented in Figure 10 according to the Foundation for Intelligent Physical Agents (FIPA) interaction protocol notation [15]. In this notation, boxes represent communicative actions: the white ones represent actions performed by the initiator of the protocol, and the shaded ones are performed by the other participant(s) (recipient) of the protocol.

This protocol allows for an iterative exchange of proposals between the PnrcAg (mediator) and the ActivityAg agents. The PnrcAg calls for proposals and stores the incoming proposals from the ActivityAg agents. Then PnrcAg proposes an agreement, and ActivityAg can accept this agreement, makes another proposal, or sticks to its lines.

As it is a cooperative interaction, parties try to make proposals to reach a consensus. Faced with different proposals from the parties, the mediator can either propose a new agreement or notify a failure or a success of the negotiation process.
4.3.2 Negotiation Model

The negotiation model of this phase is a model for bilateral negotiation about two quantitative variables, the water level and the water salinity. These variables are not independent, so we cannot use the multiattribute utility to compute an agent’s scoring function as in the Farantin model [16]. Therefore, the negotiation model is based on satisfaction values for a value of water level and a value of water salinity.

We have determined these satisfaction values with Camargue experts for each ActivityAg and periods according to rice cropping. Table 1 shows the different satisfaction values for each ActivityAg and for the rice-cropping period (April to September). Faced with a couple (level, salinity), the activity agents have at their disposal a preference scale and can revise their initial goals to come to an agreement or revise them to increase the efficiency of all agents. This negotiation can be characterized as a worth-oriented domain (WOD) negotiation [17].

Therefore, each ActivityAg has its satisfaction matrix, which will allow it to put forward proposals and evaluate the mediator’s proposals. Each proposal defines water level and water salinity values for a given period. Note that each ActivityAg does not inform the other parties of its satisfaction values, which is private knowledge.

The negotiation process is as follows:

- First proposal: The ActivityAg chooses a value couple with a maximum score in the satisfaction matrix corresponding to the studied period. If more than one couple presents the same score, the score of the neighboring couples determines its choice.
- Reply to a proposal of the mediator: To reply to a proposal of the PnrcAg mediator, the ActivityAg searches for the corresponding index in its satisfaction matrix. If this satisfaction index is superior or equal to the maximum score, ActivityAg accepts this proposal. The maximum score is initialized at the maximum value: 5. Otherwise, ActivityAg selects the position closest to the mediator and not yet proposed among the couples with a superior or equal score. If no couple matches with these two criteria, the agent sticks on its line and decreases the maximum score desired.

4.3.3 Agent Behaviors

To perform interaction protocols, for each agent concerned, we have to define behaviors. To specify an agent’s behaviors, we have adopted the agent behavior representation (ABR) notation defined in our laboratory [18]. This notation is a state transition graph with different types of states and transitions (Fig. 11). It permits one to describe how an agent behaves according to changes in its environment or interactions with other agents.

State types in ABR notation are as follows:

- Initial and final state: states indicating the start and the end of an ABR graph.
- Elementary action state: represents simple action (excluding communication) undertaken by an agent.
- Communication state: represents the act of sending a message to another agent. Such state will result in external transition in the agent that receives this message.
- Composite action state: enables recursive definition. Such a state denotes a complex action requiring another graph to be described. For example, the state labeled knowledge update is complex enough to be described by another ABR graph.
- Unlimited wait state: specifies that an agent must keep waiting until a message arrives. This enforces strong synchronization of the agents’ actions.
- Limited wait state: the agent will wait for some time, and if no message arrives before that time, an internal transition is issued to leave this state.

Transition types in ABR notation are as follows:

- Internal transition: outcome of an action state. Depending on its value, different sequences of actions can be activated.
- External transition: associated with a message arrival. Depending on the message content, different states are activated.

Figure 12 presents, in ABR notation, the behavior of the ActivityAg in this negotiation process.

Having received all proposals of the ActivityAg, the PnrcAg mediator compares the values of each element of the proposal. An agreement is reached when the difference between two values does not exceed the average of all values proposed by more than 10%. A failure is detected when no agent has modified its positions during two iterations. In all other cases, the mediator proposes a consensus, composed of the average for each of the values of the couple.

4.3.4 Negotiation Balance

The contract, defined at the end of the negotiation (Fig. 5), presents different satisfaction indexes for the different activities. Nevertheless, the results that have been obtained are situated among the optimal solutions for the group.
Table 1. Activity agent satisfaction values for rice-cropping period

<table>
<thead>
<tr>
<th>Water Level (cm)</th>
<th>Salinity (g/l)</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>35</th>
<th>&gt;35</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;-30</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>-10</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>0</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>20</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>40</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>&gt;40</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>&lt;-30</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>-10</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>40</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>&gt;40</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Supposing that the mediator had knowledge of all satisfaction matrices, he or she would be able to calculate the optimal solutions himself or herself by simply adding the scores. We have not chosen this solution since it limits the agent’s autonomy and prevents the implementation of different strategies between the activities.

4.4 Interactions and Agent Models for the Contract Realization Phase

The contract realization phase deals with both models: the hydrologic one to make hydraulic computations and the social one to make decisions about the hydraulic management.

4.4.1 Negotiation Process Overview

Each month, when the first part of the hydrological cycle finishes, HydroAg sends to DikeManagAg the current states (salinity and level) of the Vaccarès and of the sea and sends to AssoDrainAg agents the total amount of water they have to drain. These agents are able to work in coordination to define the action plan in order to fulfill the contract.

DikeManagAg manages this process since it is able to compute the Vaccarès state according to the inputs of freshwater (drainage water) and to the number of sea dike gates that are opened. Figure 13 shows the RespectContrat protocol used to manage this coordination.

Upon request from the DikeManagAg, each AssoDrainAg proposes the amount of water it wishes to drain.
Figure 12. ActivityAg behavior in the phase 1 negotiation process (CommissionEau)

Figure 13. RespectContrat protocol for DikeManagAg and AssoDrainAg coordination

Figure 14. AideDrainage protocol for the AssoDrainAg coordination

toward the Vaccarès system. Then DikeManagAg tests if the contract can be fulfilled. In this case, the AssoDrainAg proposals are agreed on; otherwise, DikeManagAg rejects the proposals telling AssoDrainAg how to modify their proposals.

If the AssoDrainAg agents have to decrease their proposals, they are able to help each other (polderized associations can pump water for other associations) with the AideDrainage protocol (Fig. 14).

This process ends (failure in Fig. 11) when a solution is found or when there are no new proposals. Then, DikeManagAg sends the action plan to HydroAg, which is now able to compute the final state (water level and level of salinity) of the Vaccarès system for the current month.

4.4.2 Agent Models

We define an agent model for each agent type (DikeManagAg and AssoDrainAg) involved in the contract realization phase. An agent model consists of a plan model and a belief model.

- The plan model describes the plans that an agent may use to achieve its goals. Each plan is a graph, which describes

the agent behavior when it achieves a goal or when it reacts to an event.
- The belief model describes the information about the environment and internal state that an agent may use and the actions it may perform. In this model, the acquaintances (set of agents interacting with the agent) are defined.

In the contract realization phase, DikeManagAg plays an essential role. So, we present here a part of its agent model.

DikeManagAg behavior. This agent leads the negotiation with the AgAssocDrain for the contract fulfillment. Figure 15 presents DikeManagAg behavior in the negotiation according to this notation. First, DikeManagAg asks for AssoDrainAg proposals (N1-CFP) and stores them when received (N3). Depending on these proposals, it is able to test if they allow the contract (composite state N4)
to be fulfilled. In this case, it sends an agreement to the AssoDrainAg (communication state N8); otherwise, it stores the current solution, tests if the process ends (N5), and, if not, rejects DikeManagAg proposals. When no solution is found (N12 or N13 states), it defines the possible opening mode closer to the defined contract and sends a failure message (N7) to the AssoDrainAg.

DikeManagAg beliefs. To test if the contract is fulfilled, DikeManagAg needs to know the behavior of the Vaccarès system (described in the hydrological model in the SysVaccare class) and the exchange rules between the Vaccarès system and the sea (DigueMer class). A RespectContrat class (Fig. 16) is used to model the DikeManagAg search for a solution.

4.5 Coupling between Social and Hydrologic Models and Global Dynamics

The HydroAg agent is in charge of the coupling between this model and the hydrologic models. This agent activates the dynamics of the hydrologic model to compute new states of the ecosystem (water and salinity levels of Vaccarès) in taking into account climatic conditions, as illustrated in Figure 6.

Concerning the contract realization phase, the HydroAg agent transmits to the AssoHydroAg agent of each catchment basin the quantity of water to drain and transmits to the DikeManagAg agent the new states of the Vaccarès and the sea level, taking into account the climatic conditions.

In the same phase, the HydroAg agent also activates the hydrologic model to compute the new ecosystem states (Fig. 7) to take into account the management decisions made by the other agents of the social model. These decisions concern the decided quantity to drain by each AssoDrainAg and the modalities of dike opening decided by the DikeManagAg.

The sequence diagram of Figure 17 shows a general view of the agent interactions in the simulation cycle for the contract realization phase. This diagram specifies the coordination process between the PhrcAg, DikeManagAg, and AssoDrainAg agents and the role of the HydroAg agent to compute (hydrologic model) and inform the social model agents of the new ecosystem states, which take into account management decisions resulting from this coordination process.

5. Prototype

To implement our modelization, we have used the MAJORCA platform developed at LSIS Laboratory. This platform integrates the JESS rule engine [19] and allows the coupling with Java objects and complies with the FIPA agent communication language (ACL) recommendations [15].

5.1 System Architecture

The system architecture includes service agents as proposed by MAJORCA and “Camargue” agents organized in three modules (Fig. 18):

- The water council (CDE) module is composed of three activity agents (fishing, agriculture, protection) and a PhrcAg agent. It implements the definition phase of the contract. When this phase is finished, the PNRC agent transmits the contract to the DikeManagAg agent responsible for its realization.
- The coordination module includes all the agents involved in the fulfillment of the contract (i.e., seven AssoDrainAg agents and the DikeManagAg agent). This module receives the hydraulic balances from the hydro module and sends back the management decisions made by its agents.
- The hydro module is composed of a single agent, HydroAg, which establishes the link between hydrologic and
The role of agent names service (ANS) consists of answering a set of requests concerning the recording of an agent and the demands of registered agents’ addresses. The agent directory facilitator (DF) holds the list of the various agents present in the system with their competence.

5.2 Agent Implementation

General software architecture. The different agents of our prototype are implemented with the MAJORCA platform. The agent behaviors are programmed in JESS rules, and complex computations are performed in Java. For

Figure 16. DikeManagAg: RespectContrat class

Figure 17. General agent interactions in the simulation of the contract realization phase
example, considering the AssoDrainAg agent, a Java class is used to compute the different proposals of drainage during the coordination. Figure 19 illustrates the software architecture of the AssoDrainAg agent with its implementation choices. In the following part, we present some implementation details.

**Knowledge implementation.** The main part of the agent’s knowledge is implemented in JESS. Appendix A (code 1) presents a part of the implementation code for the AssoDrainAg agent.

**Behavior implementation.** All the agent behaviors are specified in ABR graphs. These graphs are almost automatically (80%) translated in Jess/Clips rules (each edge and each state of the graph become a rule). Table 4 presents, for each type of agent, the number of instances of this agent in the system, as well as the name and the type of its behavioral plans. We consider two types of plan: RP = role protocol for interaction between agents, and LP = local plan for internal agent behavior. For each RP plan, we specify the other agents concerned with the plan.

Appendix B develops the main behavioral plans of the AssoDrainAg agent. Appendix C (code 2) presents a part of the code of the CoordinationDrainage plan used by each AssoDrainAg to interact with the DikeManagAg.

5.3 **User Interface**

A graphic interface makes it possible to test different simulation scenarios. This user interface (Fig. 20) allows the initialization, launch, and recovery of the results of contract elaboration and realization phases simulation:

- **Initialization.** At the initialization stage, the customizable data of the contract elaboration phase are the activity agents’ satisfaction matrix and their weighting. For the contract realization phase, the modifiable parameters are the characteristics of the drainage association agents (capacities of pumping, surfaces by type of culture), as well as the hydrological parameters (sea level, level of rain, and evaporation for each month of simulation as well as hydro-saline status of the Vaccarès system before the simulation).

- **Launching.** All these data correspond to the basic knowledge of the agents, which are in charge of launching the simulation. This simulation is made phase by phase with the possibility of input the contract to be respected for the contract realization phase. *[*PLS. CLARIFY SENTENCE*]*

- **Results.** For the first phase, the results can be observed per period (drawn up contract and indices of satisfaction of the activities) and month by month for the second (hydro-saline status of the Vaccarès, the water quantities drained and pumped by the associations and the total system, counts of the gate opening of the sea dike, and the exchanges between the sea and Vaccarès system).

A graph allows the comparison between the contract, established during the elaboration phase or input by the user, and the level and salinity of the Vaccarès system, obtained at the time of the realization phase.

6. **Validation and Simulation Results**

6.1 **Validation Results**

To explore the scenario about this system behavior, we need to validate our model. Validating models of
ecological systems is not an easy task: most modeled entities are not well known, and available data often do not match the research goals [20]. In our case, the Vaccarès system’s water depth and salinity are relatively well known, but there are sparse data concerning the hydraulic management and global hydrological balances.

To compare the simulation results with the real system behavior, we only have a 3-year data series. In this validation phase, the contract is initialized with the real states of the Vaccarès system along the simulation period (1994-1996), and the agents try to fulfill this contract.

Table 5 shows model results and field data of hydrological balance. In this table, Field corresponds to hydrological balances from Gindre, Heurteaux, and Vianet [21], and Model corresponds to the simulation results obtained by our simulation model.
Table 5. Hydrological balance (mm³)

<table>
<thead>
<tr>
<th></th>
<th>Irrigation</th>
<th>Drainage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td>Model</td>
<td>Field</td>
</tr>
<tr>
<td>1994</td>
<td></td>
<td></td>
</tr>
<tr>
<td>First term</td>
<td>5</td>
<td>17</td>
</tr>
<tr>
<td>Second term</td>
<td>171</td>
<td>168</td>
</tr>
<tr>
<td>Third term</td>
<td>224</td>
<td>198</td>
</tr>
<tr>
<td>Fourth term</td>
<td>8</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>408</td>
<td>402[403?]</td>
</tr>
<tr>
<td>1995</td>
<td></td>
<td></td>
</tr>
<tr>
<td>First term</td>
<td>7</td>
<td>31</td>
</tr>
<tr>
<td>Second term</td>
<td>167</td>
<td>167</td>
</tr>
<tr>
<td>Third term</td>
<td>220</td>
<td>202</td>
</tr>
<tr>
<td>Fourth term</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Total</td>
<td>399</td>
<td>408</td>
</tr>
<tr>
<td>1996</td>
<td></td>
<td></td>
</tr>
<tr>
<td>First term</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Second term</td>
<td>163</td>
<td>157</td>
</tr>
<tr>
<td>Third term</td>
<td>205</td>
<td>159</td>
</tr>
<tr>
<td>Fourth term</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Total</td>
<td>379[378?]</td>
<td>333[332?]</td>
</tr>
</tbody>
</table>

Figure 20. The user interface for scenario definition

Figure 21 presents comparisons between real system behavior (field data) and simulated behavior of the Vaccarès system state.

The simulation results demonstrate that the model is able to reproduce these data when agents try to achieve a contract initialized with the real state of the Vaccarès system. For the year 1996, the curves and the hydrological balances show a greater gap. Year 1996 was very wet, and this shows that our model overestimates the rain’s impact in satisfying the crops’ needs. For modeling purpose, crops need water depth, which is satisfied through irrigation water and rainfalls.

A better validation of our model needs a longer data series. After several simulation and result interpretations...
with hydraulic experts of Camargue, we can consider that the validation was consistent with field data and, enabling us to use this model to explore scenarios.

6.2 Simulation Results

Currently, there are many discussions about the future of the Camargue ecosystems. Both total polderization of the Vaccarès catchments and greatly decreasing rice areas are often discussed. Simulations were chosen to try to answer these essential questions.

In the following, simulations are made over the 3 years of the data we have. Climatological input data (precipitation, evaporation, sea level) and space occupancy are field data, while the contract to achieve is given in Table 6. These values result from the simulation of the contract elaboration [10]. This contract shows that there is a consensus on the stability of the Vaccarès system. The present hydraulic management, which drains land in winter and irrigates for crops needs in summer, tends toward a level stability of this lagoon [22].

6.3 The Impact of a Greater Polderization

The polderization of all of Camargue’s drainage basin is often questioned in improving water global management. These two scenarios aim at testing the impact of the drainage basin polderization to fulfill the contract [10]:

- **Scenario A.** It is the actual state where two drainage basins, Roquemaure and Fumemorte, are not polderized. Today, they drain water toward the Vaccarès lagoon (60 mm³ per year).
- **Scenario B.** In this scenario, these drainage basins are polderized, so they drain water toward the Rhône River.

Figure 22 presents, for the salinity (g/l) and the depth (cm) of the Vaccarès, the polderization impact on the Vaccarès. Scenario A is the actual polderization, in which four drainage basins are polderized, and in the scenario B, all drainage basins (i.e., six) are polderized.

Scenario B in Figure 22 is closer from contract curves than scenario A, particularly for salinity, but the climatic impact is not erased. The increase of human impact, by the way of hydraulic management, gives a better result to respect the contract, without considering other consequences.

6.4 Rice-Cultivated Area Impact

The great amount of freshwater needed for rice cropping influences the hydro-salt state of the Vaccarès system. Fluctuations of the area cultivated with rice for the past 50 years (from 8000 to 30,000 ha, 12,000 in 1996) have given the Vaccarès system a salinity between 5 and 38 g/l [8]. The future of rice cropping and, more generally, Camargue agriculture, which pays for the hydraulic management, is an ongoing problem.

With these simulations, we show the impact of land use on the Vaccarès system. Scenario A is 1996 land use (PNRC’s data); in scenario C, the rice-cultivated area is 50% higher; and in scenario D, the rice-cultivated area is 50% lower than in 1996.

Figure 23 shows the impact of the rice-cultivated area on the Vaccarès system. We consider three cases of cultivation of rice: (1) in scenario A, the rice-cultivated area is 12,459 ha (1996 data from GIS Camargue PNRC); (2) in scenario C, this area is 18,688 ha; and (3) in scenario D, this area is 6229 ha. Therefore, the variations of the rice-cultivated area have an impact on the Vaccarès system, especially for its salinity, which decreases significantly while the rice area increases. Hydraulic management is not able to diminish...
The management of human-influenced ecosystems requires defining goals and actions to achieve them. The Camargue has been the subject of many studies; but until now, few studies have attempted to make the link between hydraulic management decisions and the state of this ecosystem.

In this article, we have proposed a modeling and simulation of this ecosystem that integrates hydrological processes and human decisions. We have defined two models in interaction, the hydrologic model and the social model. The first one is an object model, which computes the hydro-saline state of the Vaccarés system according to natural factors (rain and evaporation) and human factors (irrigation, drainage, and management of the sea dike). The second one, a multiagent model, concerns the actors and decision processes involved in the hydraulic management of the Camargue. This management is defined as two phases of the life cycle of a contract: the contract elaboration phase and the contract realization phase. For each of these phases, we have proposed a negotiation model.

Based on these models, the prototype we have developed and validated with experts is an open tool allowing, through simulation, the achievement of various experiments on the management and evolution of the Camargue ecosystem. To illustrate its potential and participate in the study of the global behavior of this ecosystem, we have chosen to test different scenarios relevant to the PNRC managers. These scenarios show that the realization of the contract affects the drainage association management and that management of the sea dike plays an important role in the contract realization phase. In particular, the polderization of associations that are not currently polderized facilitates the realization of the contract by distributing at best the pumping effort on associations.

The aim of this research was to contribute to better understanding the dynamics of this strongly human-influenced ecosystem and to provide a simulation tool permitting us to investigate various scenarios about the evolution of this ecosystem. With the relevant simulation results we have obtained, we have achieved this purpose. These simulation results and their validation with the various main actors of this ecosystem management allow us to consider that the simulation tool we have developed is a starting point for the development of an EDSS to define future investments, provide management rules related to this ecosystem, and support the dike manager in his or her job.

To transform this simulation tool into an EDSS for the hydraulic management of the Camargue, we have to detail and support the interaction between the decision maker and the simulation tool, before, during, and after simulation. The time step in the simulation is currently a month; to take into account the consequences of strong rains, the time step may have to be lowered to a week or a day. Then we also have to couple this simulation model with a Camargue GIS that has just been developed. We are currently working on these perspectives in collaboration with the PNRC.

Finally, this research concerns an example of coordination among agents in the very specific context of the Camargue ecosystem. But we have shown that the multiagent approach is really relevant to model and simulate such strongly human-influenced ecosystems. This modeling is based on two coupled models, one for the dynamics of the ecosystem (an object model) and the other to specify the dynamics of the human influence (a multiagent model). To specify these models and its coupling modalities, we have defined our own methodology mainly based on the general AOM multiagent systems methodology, extended with the ABR graphs notation to specify behavioral plans. We are currently working on the generalization of this methodology to model and simulate, according a multiagent approach, such human-influenced ecosystems in the specific perspective of decision support system development. This methodology definition is also associated with the definition of a generic multiagent software architecture with specific functionalities adapted to the development of such decision support systems.

Figure 23. The impact of the rice-cultivated area on the Vaccarés system

7. Conclusion

The management of human-influenced ecosystems requires defining goals and actions to achieve them. The Camargue has been the subject of many studies, but until now, few studies have attempted to make the link between hydraulic management decisions and the state of this ecosystem.

In this article, we have proposed a modeling and simulation of this ecosystem that integrates hydrological processes and human decisions. We have defined two models in interaction; the hydrologic model and the social model. The first one is an object model, which computes the hydro-saline state of the Vaccarés system according to natural factors (rain and evaporation) and human factors (irrigation, drainage, and management of the sea dike). The second one, a multiagent model, concerns the actors and decision processes involved in the hydraulic management of the Camargue. This management is defined as two phases of the life cycle of a contract: the contract elaboration phase and the contract realization phase. For each of these phases, we have proposed a negotiation model.

Based on these models, the prototype we have developed and validated with experts is an open tool allowing, through simulation, the achievement of various experiments on the management and evolution of the Camargue ecosystem. To illustrate its potential and participate in the study of the global behavior of this ecosystem, we have chosen to test different scenarios relevant to the PNRC managers. These scenarios show that the realization of the contract affects the drainage association management and that management of the sea dike plays an important role in the contract realization phase. In particular, the polderization of associations that are not currently polderized facilitates the realization of the contract by distributing at best the pumping effort on associations.

The aim of this research was to contribute to better understanding the dynamics of this strongly human-influenced ecosystem and to provide a simulation tool permitting us to investigate various scenarios about the evolution of this ecosystem. With the relevant simulation results we have obtained, we have achieved this purpose. These simulation results and their validation with the various main actors of this ecosystem management allow us to consider that the simulation tool we have developed is a starting point for the development of an EDSS to define future investments, provide management rules related to this ecosystem, and support the dike manager in his or her job.

To transform this simulation tool into an EDSS for the hydraulic management of the Camargue, we have to detail and support the interaction between the decision maker and the simulation tool, before, during, and after simulation. The time step in the simulation is currently a month; to take into account the consequences of strong rains, the time step may have to be lowered to a week or a day. Then we also have to couple this simulation model with a Camargue GIS that has just been developed. We are currently working on these perspectives in collaboration with the PNRC.

Finally, this research concerns an example of coordination among agents in the very specific context of the Camargue ecosystem. But we have shown that the multiagent approach is really relevant to model and simulate such strongly human-influenced ecosystems. This modeling is based on two coupled models, one for the dynamics of the ecosystem (an object model) and the other to specify the dynamics of the human influence (a multiagent model). To specify these models and its coupling modalities, we have defined our own methodology mainly based on the general AOM multiagent systems methodology, extended with the ABR graphs notation to specify behavioral plans. We are currently working on the generalization of this methodology to model and simulate, according a multiagent approach, such human-influenced ecosystems in the specific perspective of decision support system development. This methodology definition is also associated with the definition of a generic multiagent software architecture with specific functionalities adapted to the development of such decision support systems.
8. Appendices

These appendices give some details of the prototype implementation with the MAJORCA platform.

Appendix A (Code 1): Implementation of the AssoDrainAg Agent

The code 1 presents a part of the implementation code for an AssoDrainAg agent named “Sigoulette.” We can see that this association can pump up to 3,000,000 m³/month and that no any other association can reply to a drainage demand to help it. Note the possibility to change the drainage network structure—for instance, changing the pumping capacity of a drainage association.

Appendix B: AssocDrainAg Behavioral Plans

We present in this appendix some behavioral plans of the AssoDrainAg specified in ABR notation.

---

Code 1. Knowledge of the AssoDrainAg “Sigoulette”
Plan **CoordinationDrainage**. This plan permits the coordination between AssoDrainAg and DikeManagAg (Fig. 24). AssoDrainAg computes the water quantity to drain (by gravity) for the month and proposes it to the DikeManagAg (state 2). Depending on the DikeManagAg reply, if this quantity is not accepted, the AssoDrainAg has to reconsider this quantity (composite state N4) or store it (N5/N7).

Plan **NvleQuantite**. This plan (Fig. 25) develops the composite state N4 of the previous plan. AssoDrainAg has to define a new water quantity to drain in the Vaccarès system. If its pumping capacity is not sufficient, it can ask for help from another AssoDrainAg (N3).

Plan **AideDrainage (client role)**. This plan develops the composite state N3 of the previous plan (Fig. 26).

**Appendix C: Implementation of the CoordinationDrainage Plan**

Code 2 presents a part of the implementation of the CoordinationDrainage plan used by each AssoDrainAg agent to interact with the DikeManagAg agent.

In state 2 of the plan, the AssoDrainAg sends its proposal to the DikeManagAg. This communication action is performed by the first rule of this code, which finishes with the insertion of a result fact in the agent knowledge base (assert command). This fact permits the activation of the second rule, an internal transition rule (state 2 to state 3). The AssoDrainAg is now in a wait state.
Figure 26. AideDrainage plan (client role)

Code 2. Part of the implementation of the CoordinationDrainage plan of the AssoDrainAg

20 SIMULATION Volume 81, Number 3
9. Acknowledgments
The authors thank Alain Dervieux and Bernard Picon of the DESMID Laboratory and Julien Serment of the LSIS Laboratory for their contribution to this research. This research has been developed in collaboration with the DESMID CNRS laboratory and has been supported by the PACA Regional Council.

10. References

Bernard Espinasse is *POSITION* at LSIS (UMR CNRS 6168), Université d’Aix-Marseille, Domaine universitaire de Saint Jérôme, Marseille, France.

Nathalie Franchesquin is *POSITION* at LSIS (UMR CNRS 6168), Université d’Aix-Marseille, Domaine universitaire de Saint Jérôme, Marseille, France.