Advances in Environmental and Ecological Modelling

1999, Elsevier, Paris, pp 113-122

An environmental modelling approach. The use of multi-agent simulations

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Résumé

S'agissant de l'horizon à long terme, du futur de l'environnement et des choix qui gouvernent son évolution, il est montré que la simulation à partir des systèmes multi-agents est potentiellement très riche. Cette méthode de simulation est capable de modéliser des processus d'interaction entre les agents aussi bien en termes de dynamique sociale et dynamique naturelle. Cette méthode devrait également permettre d'analyser de façon fine plusieurs questions de base dans l'évolution des relations sociétés-nature.

1. Introduction

In the field of sustainable development, the problems of access and use of renewable resources are key issues. Scientists working in this area need to examine the interaction between ecological and social dynamics. Indeed, for many years, this question was examined either exclusively from the angle of 'an ecological system subject to anthropic disturbance' or, alternatively, from the angle of 'a social system subject to natural constraints'. In the first case, scientists make a careful description of the dynamics of the resource, with management constituting a definition of the various forms of anthropic exploitation which can be sustained over the long term by this resource. Social dynamics are summarized in terms of the type of resource exploitation they entail. In the second case, researchers generally concentrate on the problem of resource usage, placing themselves in the position of an isolated economic agent who wishes to maximize the benefits obtained from a restricted resource and placing the collective use of common resources within a framework of competitive exploitation.

For example, Hardin [14] presented the concept of the tragedy of the commons: according to the author, the management of common assets, renewable resources in particular, inevitably leads to over-exploitation of the resource and its ultimate disappearance. As the profit gained from the use of resources is individualized while costs are shared, it is in the interest of each individual to exploit the resource to a maximum. This conclusion has had a major impact on renewable resource management, pointing to the development of private property as a means to avoid over-exploitation. Hardin's reasoning has been vehemently criticized, in particular by Berkes et al. [3], who demonstrate that it establishes an abusive relationship between common property and free access to this property. From a formal point of view, Hardin's hypothesis has been modelled by game theory and it has been demonstrated that if a renewable resource is given the status of common property, the outcome is not necessarily that of the tragedy of the commons, provided that simple imitation behaviours [23] or sensitivity of the resource to social interactions [6, 27] are represented.

Unlike the ecological approach or the economic approach, both of which postulate hypotheses of equilibrium and optimization to formalize situations of competition or interaction, other scientific paradigms see renewable resource management in a different light, integrating the ecological and social dimensions differently in terms of their dynamics and their interactions.

We will focus on the methods which take into account the collective rules governing access to resources. Groups of users establish rules and institutions to maintain resources and uses over long periods. There are many definitions of the institution – we will mention two, that of Ostrom [25] "a set of rules in use" and that of Weber [28] "any agreement between two individuals or groups which applies to others beyond these two individuals or groups".

For example, the water tribunal in Valencia (Spain) has been coordinating the various actors involved for the last thousand years [12]. These rules are applied at the various levels that Weber [28] gives to the concept of the renewable resources appropriation regime:

- access to resources and control of access;
- use of resources;
- representations or systems of behaviour;
- resource distribution mechanisms;
- resource transfer mechanisms.

We want to study the viability of the system of interactions between ecological dynamics and social dynamics via the rules and institutions that a society establishes for itself and enforces. The contract theory, the competing market theory and the convention theory are just a few of the many theories and models developed by economists, anthropologists and sociologists to represent the way in which agents coordinate their activities.

In this paper, we present the multi-agent modelling tools which we believe to be appropriate for the representation of ecological and social dynamics, which state modelling problems in terms of representations, communication and controls, and which provide a good exploratory modelling medium. We will then examine modelling methods for collective management of common property using multi-agent systems. Finally, we will discuss how these simulations can be used to study the problem of long-term resource management.

2. Multi-agents

The theory of agents or of multi-agent systems [10] is a computer theory which seeks to apprehend the coordination of competing independent processes by means of an anthropomorphic metaphor which is exploited and sometimes over-exploited by scientists in this field.

An agent is thus a computer process, something between a computer program and a robot, which can be considered as autonomous since it is capable of adapting when its environment changes. An agent in the computer sense should not be confused with an economic agent, though we can create computer agents representing economic agents. In the rest of this article, people in the real world will be called actors and entities of the artificial world will be called agents. A typical and topical example of an agent is a navigating assistant, a computer program which explores a network of computer data (Web), which chooses possible pathways by a system of markers, which downloads relevant information at times when the network is not saturated so that the user can navigate much more easily and efficiently in a personalized data base. Because the content and structure of information bases is changing all the time and because the assistant has to adapt to these constant changes, we can say that it is autonomous.

A multi-agent system comprises a set of computer processes taking place simultaneously (several agents living at the same time, sharing common resources and communicating with each other). The key to the theory of multi-agent systems lies in the formalization of the necesary coordination between agents. The agent theory is thus a theory of control – what sort of hierarchical relationships exist between agents?, how are they synchronized? – and of communication – what type of messages do they send each other?, what is the syntax of these messages? – for which it proposes elaborate formal expressions.

The theory of multi-agent systems has applications in artificial intelligence where it can be used to reduce the complexity of a problem-solving process by dividing the necessary knowledge into sub-assemblies, associating an independent intelligent agent to each of these sub-assemblies and coordinating the activities of these agents. This is known as distributed artificial intelligence. This theory can be applied, for example, to the supervision of an industrial process in which it implements the common sense solution which involves coordinating several specialized supervisors rather than calling upon a single omniscient supervisor. This principle of knowledge distribution can be implemented even more systematically to solve famous combinatory problems such as the Fifteen Puzzle or the Tower of Hanoi by making all parts of the puzzle independent and by giving them a very simple behaviour pattern expressed in terms of avoidance or attraction. This is called eco-resolution [8].

The theory of multi-agent systems overlaps with a type of modelling found in ecology, called individual-based modelling, which studies the overall behaviour of a population where the processes involved are exclusively individual and which is used for computer simulations [16]. Indeed, these models are quite naturally able to take into account major ecological factors, such as differences between individuals or their type of relationship with space. The meeting of these two formalisms, the multi-agent formalism and the formalism of individual-based modelling is, in our view, highly enriching in both directions. First, ecological problems represent an inexhaustible source of questions about interactions which are simple to state and difficult to resolve [13, 17]. Second, the theory of multi-agent systems not only offers pertinent and powerful formalization tools, but also provides a better framework for computer simulations. Indeed, multi-agent modelling sometimes produces reproductions of reality without any form of abstraction; by placing emphasis on questions of control and communication, the theory provides a means to express explicitly the body of hypotheses that modelling aims to explore.

Lastly, to pursue an anthropomorphic metaphor, the theory of multi-agent systems represents agents, i.e. computer processes, endowed with qualities of perception, mobility, reflection and capable of defining objectives, constructing strategies, etc. Our aim is to examine the opportunities for developing formalisms for control and communication, and for strategies and individual representations, with a view to performing computer simulations to explore questions of collective renewable resource management. Here again, the hope is that the encounter will prove fertile in both directions.

3. Individuals and groups in multi-agent modelling

The application of the theory of multi-agent systems to the simulation of social phenomena is generally associated with the current of sociological thought called 'methodological individualism' [15, 19] which considers the single individual as the elementary unit and the atom of society [30]. The similarity between the multi-agent and the sociological theory lies in the bottom-up approach of multi-agent systems [9]. However, it can be misleading to liken individuals of a society to agents of a multi-agent system since social groups or institutions, with their operating rules and standards, can also be seen as agents [20]. Agents are guided by constraints and rules expressed at group level: they are nothing more than acting entities placed in a dynamic environment.

This simple remark, quite logical in the context of modelling by a multi-agent system, indicates how the simple duality between individualism and holism can be brought into doubt, and this is a major concern both for scientists studying renewable resource management and researchers studying multi-agent systems:

• individuals, who are products of history, are governed by collective values and rules;
• collective rules and values evolve by interaction between individuals and between groups;
• individuals are neither similar nor equal, but have a role and a social status.

How do individuals construct this collective whole? How is an institution created? In return, the individual cannot be viewed as an autonomous entity independent of his social environment. How are individuals constrained by the collective structures they have created for themselves and how do they cause them to evolve? How many degrees of freedom are available for individual practices? Here are some of the questions that multi-agent systems can explore in the following terms: how are collective structures created and operated by agents who have varying representation capacities, who exchange information, goods and services with each other, who draw up contracts and who are living in a dynamic environment which reacts to their actions? Our starting point is the fact that these questions can be answered using the theory of multi-agent systems, i.e. in terms of control and communication, and that a highly illuminating illustration of this can be found in the field of renewable resource management.

4. Modelling of renewable resource management

Simulating the management of common resources raises the problem of the interaction between sets of agents and dynamic resources. Empirically, several different methods for modelling these interactions can be distinguished. We will illustrate our remarks with examples taken from simulations of water management in irrigated areas.

The first modelling method places emphasis on the cognitive processes or representations which determine the interaction between agents and resources. Each agent makes his own representation of the resource and acts upon it accordingly. By doing so, he transforms this resource for others. This interaction modelling is similar to what economists call externalities. For example, in the case of irrigated areas, each of the farmer agents has a specific representation of his plot of land and of his water requirements. Some, who see their plot as a simple piece of property, may be quite flexible regarding irrigation schedules, whereas others, who see their plot as a means to earn their living, will be much stricter on this point. For example, the start of irrigation may be delayed by certain agents because their plots are not ready or, in the case of collective pumping of river water, consumption may vary from one agent to another. We study a problem of common renewable resource management by comparing the representations and hence the different actions arising out of these representations, which may or may not give rise to satisfactory usage for all agents. We can speak of coordination by the environment.

A second method focuses on the simulation of management in social networks. Here, the relationships between men and resources are formulated as relationships between men with respect to resources. Multi-agent systems can be used to simulate agents who exchange messages within networks, called acquaintance networks. It is thus possible to simulate exchanges of information, services, contracts and agreements between agents. For example, in the case of irrigated areas, farmer agents can send messages to keep each other informed about water levels in the plots, to request or offer services, or to exchange agent's addresses. We can simulate conversations between agents who, when they think that their plot cannot wait its turn for irrigation, may request permission to irrigate and who, when it is their turn, may accept or refuse requests from others. We thus show [1, 2, 5] that the number of dry plots in an area may depend closely on the structure of these social networks.

Lastly, we would like to suggest a third method for modelling interactions between groups of agents and common resources. To go one step further in the characterization of the individual-society loop, we propose to represent 'mediator' objects or 'common referents'. These are objects which are both an individual and a shared representation, which tend both to create the social group and to be the expression of its existence. They include collective memory, myths, markets, divinities, symbolic places or items, i.e. objects that people are constantly constructing and perceptions that guide or constrain the practices of these people. There is reification, not of the collective whole, as the holist point of view would see it, but of objects which are a sign of the whole. Through the perception of these objects, each agent sees himself as a member of the whole and thus contributes to the creation or continuation or modification of this whole. This has been conceptualized by Gilbert [11] as second-order emergence. More precisely, the conception of mediating object can be limited here, for the moment, to the representation of institutions. An illustration of this is taken from the work of an anthropologist and a modeller, Lansing and Kremer [18], who have studied problems of water management in Java. The drainage basin under study is divided into several portions called subaks. Sharing of water among the subaks is based on a religious calendar which organizes rituals around several water temples. It is during these rituals that water usage rights are transmitted. By simulating this organization (the agents use water in accordance with this religious calendar) and by comparing it with other water management methods (e.g. all agents use water at the same time, or in a haphazard manner), the authors show that this type of coordination corresponds to an agricultural optimum for water usage.

In short, we think that multi-agent systems offer formulations which are capable of taking into account several thought models for collective management of renewable common resources. Multi-agent systems, which provide the possibility of modelling representations, modes of communication within networks, individual or social controls, imposed or constructed controls and interactions, provide a good means to simulate forms of coordination observable in the field.

5. Companion modelling and patrimonial approach: the very long term

One of the classic uses of simulation is for prediction, but this is not the option we have chosen. The very long term cannot be predicted in the economic and social field, though it is partially decidable. This is the hypothesis underlying the 'patrimonial approach' [22, 24]. "Because the very long term is beyond the scope of prediction, if we wish to take it into account in the analysis of environmental problems, we must give ourselves very long-term reference points or objectives to guide the possible or impossible pathways of development. The long-term approach must inevitably be based on a scenario" [29]. Because the rules result from the interaction between actors, they are legitimized in the eyes of all actors and they incorporate particular perceptions. It is on the basis of a shared conception of how the present situation should evolve that actors are able to 'decide' very long-term objectives, on the basis of which the scenarios which enable these objectives to be reached can be discussed. The entire mediation approach presupposes the establishment of an initial situation, in Rawls' sense, in which the actors are clearly informed of the issues which divide them and of their common dependence upon a solution to the problem at the origin of the mediation process. The challenge of the initialization phase is to enable actors to express their perceptions of the present situation and of its evolution. When a 'map of perceptions', all equally legitimate and equally subjective, has been established and discussed, the actors are asked to discuss the acceptability of prolonging existing tendencies.

How can simulations be involved in this process, i.e. how can they help actors to govern? We are seeking to develop the idea of companion modelling using multi-agent systems. The ideas which follow constitute an approach which is currently being implemented but which, as yet, has only been partly tested. Although it is doubtless original in its use of multi-agent systems, it is an approach which has already been used by several researchers whose work has served as a basis for our studies. These researchers are Ostrom [25] and Burton [7]. For the relationship between the patrimonial approach and the placing of actors in an experimental situation through role playing, much work has been done by Mermet [21] and Piveteau [26]. Our thought framework is close to these authors and we propose to include the modelling approach with multi-agent systems within this framework. This involves a number of stages:

- Construction of an artificial world. The first classic stage, involving one or more researchers, is to gather information on the system under study. We suggest that field work and modelling be performed in unison. The task is to identify the different actors and perceptions and to use multi-agent systems for modelling. Faced with a highly complex world, multi-agent systems provide a means to identify the most acceptable form of simplification by focusing questions on problems of representations, communications and controls. Simulation raises questions in the field which provides new data for the model. Several models have already been proposed for this stage, e.g. for a fishery [4].

• Restitution. The second stage could also be referred to as validation of the cognitive model. The aim is to test the model proposed for the decision-making process. It involves a thorough analysis of the representations and interaction processes between agents. Indeed, it is difficult to explain what has been 'put into the machine'. On the other hand, it is possible to put an actor in the situation of the agent who is in the machine, with the hypotheses of representation, communication and control which constitute the model. To perform this operation, we propose to use the role-play methodology tested by the authors mentioned above. The artificial world is evaluated by plunging the actors into it, i.e. by creating a world similar to the model. These actors may be actively involved in the management system as users of the resource (farmers), regulators of this management system (managers or administrators) or observers of the system (researchers). Does the artificial world inhabited by these actors resemble the real world? The aim is to validate a simulator in the same way as, for example, a flight simulator. A good flight simulator incorporates the same components of the decision-making process as in reality, rather than simply reproducing an actual flight. This stage may be included in the initialization phase of the patrimonial approach as it provides a means to establish a map of the various types of actors, the different perceptions and interactions, and to make them into shared knowledge.

• Simulation. Simulation shows how the dynamics of the system arises out of interactions between actors with different weights and representations. We can divide this phase into two sub-phases. Initially, the simulation can be performed in the form of role play, which enables actors to validate the fact that it is indeed in the interactions between different representations that the motor driving the dynamics of the system is to be found. This first sub-phase also brings to light the different scenarios that are worth testing. Then, once this phase has been completed, the multi-agent model can be used to make simulations based on different scenarios. Simulations, both 'in ludo' and 'in silico', are also involved in another phase of the patrimonial approach in which, after long-term objectives have been defined, the various scenarios liable to lead to these objectives are tested and their results discussed.

6. Conclusion

The environment of the 21st century is within the realms of prediction, if we are talking about the year 2001. But beyond a long time-horizon, its evolution will be governed by the collective choices taken to orient present action. The definition of these long-term collective choices presupposes that agreement has been reached regarding current tendencies, that there is a fount of shared knowledge forming a basis for discussions on the future. Multi-agent systems provide a simulation method rich in potential, capable of modelling interaction processes between actors as well as between social dynamics and natural dynamics. Indeed, they use the same procedures and the same structure to treat human and non-human agents with perceptions, modes of communication and controls. They can also be used to represent individual or collective agents, whether real or symbolic, without predefined interaction dynamics. In this respect, they constitute one of the first modelling methods applicable to social sciences, not requiring massive oversimplification of a complex reality. They constitute a tool for interdisciplinary dialogue and make it possible to construct models that can be validated or invalidated socially, without claiming that they are 'true' or 'false'. Multi-agent systems, whose history is still recent, open new opportunities for exploring interactions between social and natural dynamics over the long term.

We know that, throughout our further studies, we will need to refine our answers to a certain number of basic questions:

• Is it pertinent to approach the study of the complex system of relationships between a society and the natural environment by its control and communication structures? We have made our choice known in this respect.

• Does society as such emerge from individual behaviour patterns? We know that we must escape from this dilemma and the idea of second-order emergence is an avenue we are exploring to this end.

• Should a specific methodology be developed with respect to the power of suggestion of multi-agent simulations? This question is valid for all sophisticated modelling techniques using today's powerful computer calculation, interfacing, communication and formalization capacities, and which could well be used to convince the public on the basis of considerations which show little respect for scientific truth. We have seen how the definition of companion modelling, with emphasis on role playing, provides a means to develop an appropriate methodology providing the necessary guarantees.

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