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Towards agent-based modelling of stakeholder behaviour – a pilot study on drought vulnerability of decentral water supply in NE Brazil

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Towards agent-based modelling of stakeholder behaviour – a pilot study on drought vulnerability of decentral water supply in NE Brazil

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Abstract:
While Integrated Natural Resources Management (INRM) creates a need for an integration of natural and socio-economic information, suitable approaches and tools are needed to facilitate this integration. If these tools are meant to support the decision-making process of the stakeholders, it is important that they are adapted to the needs and requirements of these end-users. One way to achieve this is the flexible and seamless direct participation of stakeholders through adequate model structures and interfaces. Participatory methods should facilitate the communication process with different stakeholders and allow for interactions between them. Models for this purpose ideally contribute to the stakeholder's understanding of the system by representing the natural water resources system in a detailed, distributed, and process-oriented manner and by including the anthropogenic influences in the system. Agent-based models represent a possible approach to INRM fulfilling the specified requirements. Such models facilitate active participation of stakeholders because of their relative descriptive clarity and the straightforward way of interpreting them. In a pilot study on agent-based model application in this context, the decentral water supply system of the municipality of Tauá in the drought-prone Northeast of Brazil has been modelled. The local population is affected by a bad water quality and a comparably simple water supply infrastructure, with distribution networks only in major towns. The research objective of the case study is to represent the decision of the water users for one or several of the available water sources depending on the availability of resources, the water quality, and the background of the water users, e.g., their economical situation. Representing the decision-making process of the agents in such a simple context is investigated in order to explore solutions based on analysing and adapting agent-behaviour, e.g. for creating Decision Support Systems. The model was designed relying on census data on water sources, quality and consumption in different situations of water availability.

Keywords: Agent-based modelling; Natural Resources Management; Water supply

1. Introduction

Developing environmental models is a demanding task because of the need to reach a ternary optimization. The modeller is supposed to have a profound understanding of the often complex environmental systems addressed in the model (a), the software developer needs to choose and master adequate software options and techniques used for specific requirements (b) and finally, a successful Decision Support System (DSS) must be based on the perspective and needs of the intended users, e.g. the stakeholders of the modelled system.

Consequently, failures in the modelling process are possible in respect to all three aspects, i.e. environment, software and user analysis. However, in the context of decision support especially a deficient user analysis is critical. Not surprisingly, stakeholders may not be willing to apply a tool that does not suit their specific needs. Only if end-users understand a DSS and its potential benefits and believe in its capacity, the DSS is a valuable tool and will help them to optimize their decisions.

Agent-based approaches offer a new chance in this context. Recently proposed multi-agent systems (MAS) have their origins in computer sciences, however, they are now widely applied in

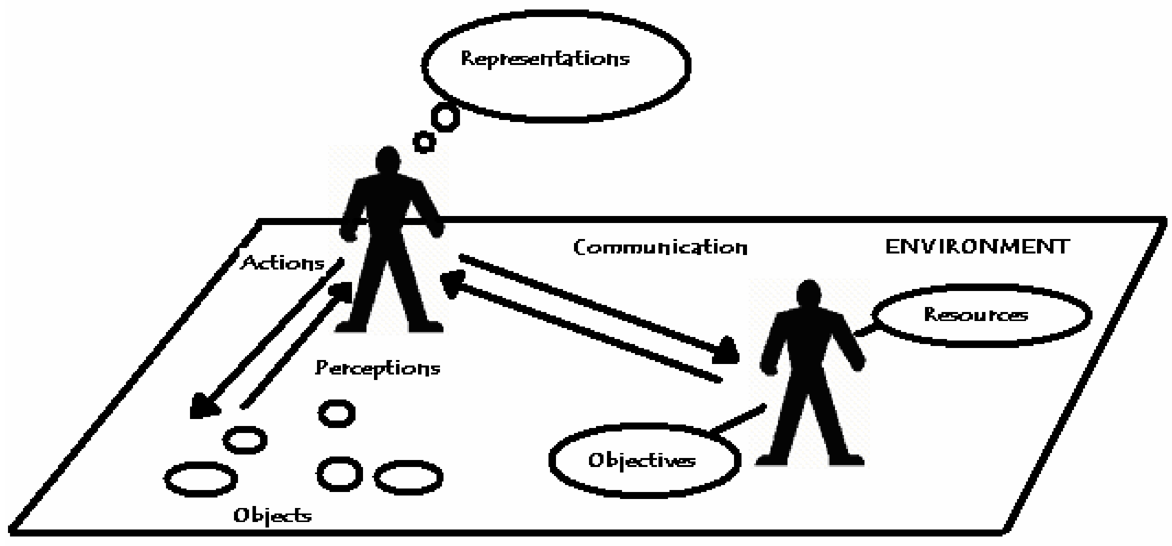

Figure 1: Schematic illustration of a multi-agent system (adopted from Ferber [1999])

a variety of disciplines for several purposes [Berger, 2004]. They consist generally of different agents, their interactions, and an environment (Figure 1).

The remainder of this paper is organized as follows. In the next section an overview of the advantages of agent-based models in the context of decision support is provided. Section 3 introduces briefly a pilot study on an agent-based model application for the municipality of Tauá in Brazil. Moreover, issues of the layout of agent-based DSS systems are discussed based on this case study.

2. AGENT-BASED DSS MODELS

Compared to other kinds of models that serve as a basis for DSS, the application of multi-agent models provides several advantages.

2.1 Ease of understanding

The aim of a DSS is not to predict the future outcomes exactly, but to improve the stakeholder's understanding of possible scenarios [Gilbert et al., 2002] leading to sound decisions. DSSs relying on agent-based models may be understood and interpreted more easily than systems built with other types of models. They consequently take into account the user's limited resources of time.

The results of the modelling process are easier to apply in practice, since the system is not translated into equations between observables [Van Dyke et. al., 1998]. Stakeholders without profound knowledge in model construction and analysis can have difficulties to interpret the parameters and statistical outputs of conventional, equation-based models or to find the connection between parameters and practical policies [Gilbert et al., 2002]. Whereas pattern recognition and analogical reasoning are quite natural and easy for humans, a differential equation is most likely not a natural metaphor for processes in the real world [Axtell, 2000]. In addition, multi-agent models do not need a large number of parameters and work mostly with time and space variability directly without average effective parameters [Van Dyke et. al., 1998].

2.2 Stakeholder involvement

Possibly the best way to realize an appropriate user analysis is to actively involve the end-users of the tool into the modelling process. In addition, stakeholder involvement increases the willingness of the participants to apply the models to real-life problems due to higher motivation and positive attitudes towards the models [Hare et al., 2002].

Because of the relative descriptive clarity of agent-based models and the straightforward way of understanding them, agent-based models facilitate stakeholder involvement [López-Pareded et al., 2005] and are often used for this purpose [e.g. Feuillette, 2003, Barreteau et al., 2001]. Such a combination is meant to exploit the advantages of multi-agent approaches to full extent, e.g., the stakeholders see the problem with the same perspective as they do in real life [Gilbert et al., 2002]. In order to realize stakeholder involvement, the models are often, but not necessarily combined with role-playing games approaches.

2.3 Integration of biophysical and social aspects

A great advantage of multi-agent models is their suitability for empirical studies of human-environmental interactions, because they handle the connection between the physical environment and the social world without problems [Gilbert et al., 2002]. Hydrological systems, for example, are coupled with the surrounding world, and anthropogenic influences have to be represented appropriately. However, hydrological models are not prepared for including socio-economic aspects.

Agent-based models offer a seemingly natural representation of entities, either individuals or institutions, as agents [Gilbert et al., 2002]. Instead of describing the behaviour of humans in abstract equations, the agents and their behaviour are represented more or less directly as conceptual entities. Agents can be equipped with simplified versions of the goals, beliefs, and capabilities of the stakeholders [Gilbert et al., 2002]. Thereby, such models provide a way to handle an enormous amount of data and knowledge about the behaviour and the motivations of the human agents as well as about their relationships with social agents [Bankes, 2002]. Moreover, since multi-agent systems are originally created for representing complex systems, they are characterized by a high flexibility and a special capacity for integration [Ferber, 1999], e.g. with Geographical Information Systems (GIS).

3. PILOT STUDY ON WATER SUPPLY IN TAUÁ

In the context of water resources, it is actually problematic that most models do not address interrelations between evolution of water resources and human development in a balanced way. Instead, the emphasis is commonly placed on one side, either on accurate modelling of the water dynamics or of the human activities.

The focus of the case study presented in this paper is therefore twofold. The aim is on the one hand to describe the natural resources as precisely as possible, and to represent the decision-making process of the water users in an appropriate manner on the other hand.

3.1. Study area and research question

The municipality Tauá in Brazil is located in the so called drought polygon, an area in the Northeast of Brazil (Figure 2) [Gaiser et al., 2003]. Tauá is among the regions with the highest water scarcity in Brazil and partly affected by poor water quality as well. The origin of the water shortage in the semi-arid area can be seen in the imbalance between the availability of natural resources, the state of development of the water supply structure, and the water demand for specific uses.

Figure 2: Position of the municipality Tauá in the federal state Ceará [De Oliviera et al., 2003]

The local population does not obtain sufficient water for their daily needs. The water supply infrastructure in the rural areas is comparably simple, lacking a public water supply. Frequent and partly severe droughts are a major problem for the decentral and autonomous water supply of the local population

The question is how the approximately 60,000 people in the area cope with these issues. The purpose of the developed agent-based model is to understand and reproduce the behaviour of a basic, decentral and autonomous water supply under drought stress. The agents in the model represent the decision of the water users for one of the available water sources.

Because Tauá has been one of the focus regions in the WAVES project (*Water Availability, Vulnerability of Ecosystems and Society in the Northeast of Brazil*), the data availability is rather good. The accessible information includes a survey conducted with the local population. This census provides data on household sizes, preferred water sources, and behaviour under different conditions, e.g., in drought and in winter time.

The model that has been developed within a research project on exploring the possibilities for modelling basic water supply systems may be used as an independent consulting tool for governmental organizations, e.g. the Ministry of

Agriculture. Three workshops within the WAVES project helped to ensure that the addressed research question suits the needs of these stakeholders.

3.2 Design of the multi-agent system

In general, the model consists of two different parts, i.e., the physical environment and the agents representing the entities living in the environment (Figure 3). The physical environment is implemented as regular grids in which the agents are located. In addition, it contains the four most important water sources, i.e., cisterns, dams, waterholes, and wells. The spatial distribution of the sources and their water capacities are estimated according to the available information, which is measured hydrological data and assumptions about the involved hydrological processes. All assumptions or results of the model have to comply with the hydrological balance of the area.

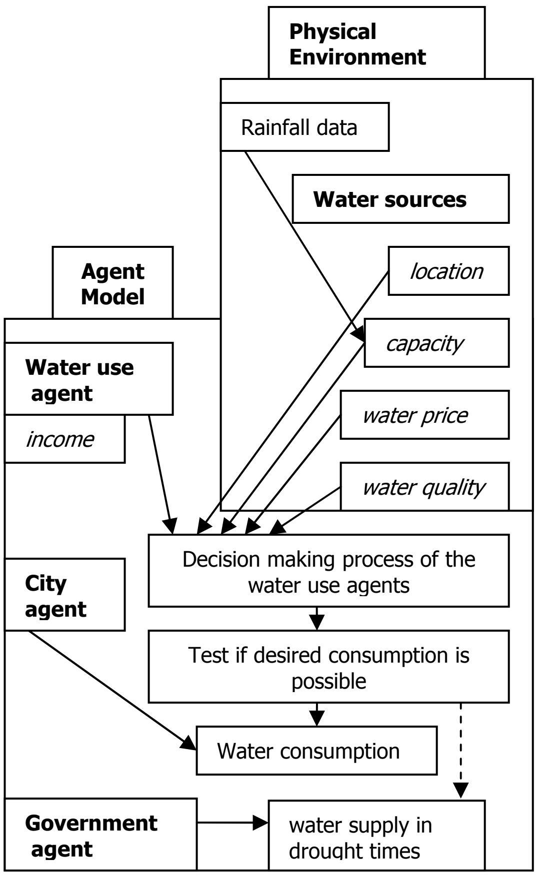

Figure 3: Design of the model

In the current version, the model contains three types of agents: For the rural areas, the water users are represented as households. The population in the city is not the focus of interest and consequently represented as one single agent with a bulk usage of water only. The third type of agent is an agent representing the government. Its functionality is limited to one action, namely providing water by water trucks in times of critical droughts.

The preferences of the water users for specific water sources are meant to be based mainly on four factors: The distance to the source as a measure for time and energy needed to get the water; the water costs per cubic meter; the water quality and the remaining capacity of the resources. Based on these four factors, an index was developed that indicates the attitude of an agent towards the different water resources. Each water source is rated for each of the four categories, and the results are multiplied to achieve the final index value.

Since it is not thought to be likely that the water consumption is identical for all the water users and in all situations, consumption is flexible depending on the assumed remaining capacity of the water sources. That is, if the agents expect the water resources to be more abundant, they consume more water than in times with scarce resources.

The model is implemented using the multi-agent platform Repast [Collier et al., 2003]. The programming language is the object-oriented language Java, extended with libraries suitable for multi-agent programming. The model is run with a monthly time step.

3.3 Results

At the current state of development of the model, its results are promising, but not reliable yet. Figure 4 illustrates the results of a model run for normal conditions, i.e., assuming the average monthly rainfall of the area (620 mm).

The graph shows the dynamics of the water sources that corresponds to the climatic input, although the total number of water users without water sources is relatively high.

The model needs some improvements as well as an enhanced validation in order to deliver more realistic results. However, its design is seen as a new approach of modelling similar decentral water supply systems that may serve as the basis for a decision-support system. The model structure allows simulating a whole variety of scenarios without difficulties such as the reaction of the system in dry years or to different economics situations, e.g., changing water prices or different financial situations of the water users. Moreover, it may be interesting to test different concepts of the decision-making process or, alternatively, the impact of governmental measures, e.g., the building of new wells.

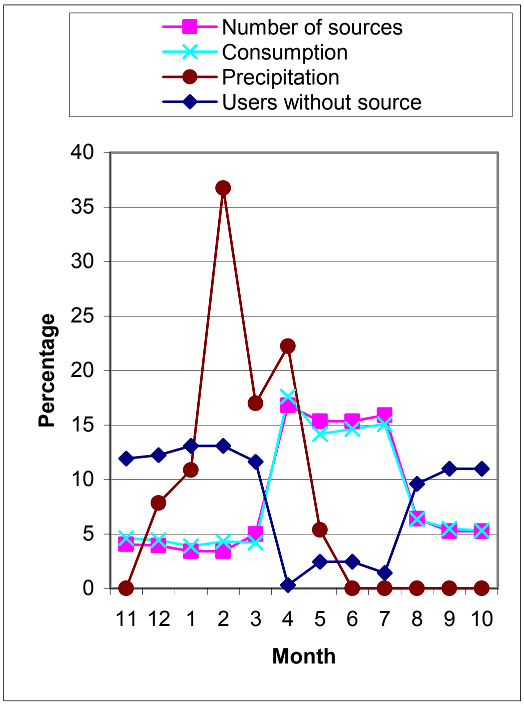

Figure 4: Monthly variation of important characteristics of the system (all values given as percentage of their annual value)

3.4 Problems and lessons learned

To look at the lesson learned while designing this pilot agent-based model may be more interesting than its first results. First of all, it has become evident that the information available in the survey was not sufficient for modelling the decision making process of the water users appropriately. The consequences for the development of DSSs are that multi-agent models do not supersede the collection of sufficient data about the social system, although they facilitate the transformation of such information into a model. Moreover, psychological and sociological concepts are needed to create a more reliable representation of the water consumers' decision making process.

In the current state of the water supply system in Tauá, the collapse of the autonomous local water supply in drought times requires expensive state interventions, mainly the provision of water by water trucks. Therefore, governmental organizations as the Ministry of Agriculture or the Department of Rural Water Supply are the intended end-users of the model. Improved understanding of the basic water supply system in the area may help to optimize investments into drought resilience.

In this pilot study, stakeholder involvement was achieved by means of a survey of the local population and by several stakeholder workshops. A further integration of the stakeholders into the modelling process is intended for the further development of the model.

A general critical issue for multi-agent models is their validation. Techniques for validation of complex models have not been established yet [Feuillette et al., 2005]. The question remains whether a general technique for validating complex models, particularly multi-agent models, has not been found yet or may not exist. Validation for modelling of scenarios is especially hard to achieve, since a comparison of the simulated data with measurements is generally not possible. However, in order to make the stakeholders trust and use the model, validation seems to be critical. Only a legitimised model is a useful tool for the discussed purposes [Barreteau et al., 2001].

As in all models of complex systems, it is hard to distinguish in case of unexpected results whether this is an implementation error or emerging behaviour of the system, since there are no a priori functional requirements of the system [López-Paredes et al., 2005]. However, understanding of the model and its outcome is a prerequisite for its further development into a DSS and for its subsequent application.

4. CONCLUSIONS

The first experiences with the discussed model are an encouragement for further work on agent-based models of basic water supply systems. Although the region under study has been subject to a great number of academic studies, a solution leading to a substantial improvement of the water supply for the impoverished population has not been established yet. The potential advantage of the agent-based model lies in the direct inclusion of the decisions of the water users.

Therefore, the study is based on a census on water use by the local population under different conditions (drought, normal, wet season). In the view of the authors, the direct representation of the water users is the highest benefit of applying agent-based modelling techniques in this case study. Agent-based modelling may lead to the development of useful rules of behaviour for increasing the resilience of water supply systems.

By analyzing the adaptation of the water users to different conditions, important knowledge can be gained for a successful management of the system in normal as well as in drought times.

Generally, identifying rules governing the behaviour of water users may belong to the contributions of agent-based models to water management. Ideally, an agent-based model has to represent the natural system appropriately and to identify the rules that determine the behaviour of the agents in the system at the same time. In addition, such a model should be tailored to the needs of the end-users, for example by making use of the ease of stakeholder involvement. Furthermore, it has to realize high user friendliness, e.g., by providing appropriate graphical user interfaces and by reducing the complexity of the system to a degree that makes it understandable for the potential users.

Careful realization of these issues may make an ABM useful for water management. However, some methodological issues are apparently critical for achieving this goal. In the context of environmental modelling, human and non-human components of the systems have to be integrated and treated with equal care. Only then the model may provide a realistic representation of the reality and be suitable for building a DSS. In general, it is crucial that the stakeholders trust the system. Therefore, the importance of validation has to be emphasised. An inherent risk of such models is that the promising-looking outcomes are trusted without proper and critical evaluation

Consequently, further research as well as interdisciplinary efforts may be necessary to create agent-based decision-support systems that provide enhanced representation of the social systems and reliable models of environmental aspects at the same time.

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