

# Agent Based Simulation in Integrated Assessment and Resources Management

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**Abstract:** Resource management problems have become more and more complex. The traditional approach to solving isolated environmental problems with technological fixes and end-of-pipe solutions has started to shift towards a more thoughtful and integrated attitude. Hence it becomes more and more important to develop appropriate means for representing the human dimension in integrated models and in the development of resource management regimes. This involves the development of integrated approaches to problem solving and thus to include as well stakeholder perspectives. Stakeholder should be included in the process of developing and adopting any resource management plan. In order to improve stakeholder-based policy design and modelling processes innovation and research is required in linking analytical methods and participatory approaches. Factual knowledge and analytical techniques have to be combined with local knowledge and subjective perceptions of the various stakeholder groups. Agent based modelling seems to be a particularly promising approach to include the human dimension into integrated assessment models and processes and thus into innovative approaches towards developing more sustainable and enduring resource management regimes.

**Keywords:** Agent based modelling, resource management, social learning, participatory integrated assessment.

## 1. INTRODUCTION

The human dimension has gained more and more in importance when dealing with resource management problems. As Ludwig et al [1993] pointed out for the case of fisheries management it seems to be more appropriate to think of resources managing humans than the converse. The current challenges in resources management are less characterized by solving well defined problems but rather by building flexible and sustainable resource management regimes. The traditional view of a sequential process of the science policy interface starting with the identification of an environmental problem from the natural science perspective, continuing with the search for a (preferably technical end-of-pipe) solution, and finally leading to the dissemination of this knowledge to decision makers has been replaced by the insight that the human dimension has to be integrated from the very being of the analysis of the problem. However, major conceptual and knowledge gaps exist how to include the human dimension into integrated assessment models and processes.

Approaches derived from economics are not process based and start further from the assumptions of an equilibrium between supply and

demand or if a rational expectations equilibrium in a collective of agents. They are in general top-down approaches and the processes / parameters are chosen such that they lead to a new equilibrium state. This is very uncommon for any natural science or engineering approach where one starts with processes and the equilibrium state (if it exists) results from the interactions. Related to the economics approach is the strong normative claim that the market equilibrium results in a Pareto optimal state for the resource allocation and that this state is this the most desirable in terms of maximizing individual and collective welfare given the availability of a limiting resource. Even if it is now readily admitted that market failures exist regarding the visibility and the value of environmental goods, current analytical approaches are yet quite limited in dealing with the complexity of real resource management problems and the dynamics of the interaction between human behaviour and the environment. Further, there are basic assumptions about human behaviour inherent in e.g. game theoretical approaches that ought to be questioned given the contradicting empirical evidence. The economics perspective covers only a part of the whole breadth of the spectrum of possible approaches to represent human behaviour [e.g. Gigerenzer and Selten, 2002]. The importance of the self-organizing capacities of local

communities has for example been noted for quite a while [Ostrom, 1990, Pahl-Wostl, 1995].

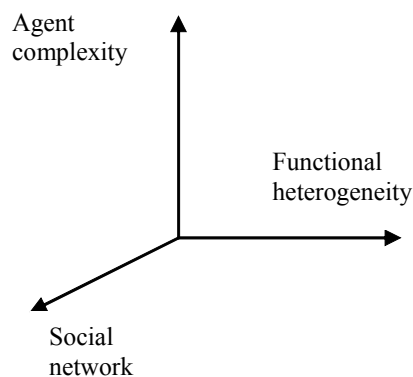
Agent based modelling (ABM) is a very promising approach to include the human dimension into Integrated Assessment Models in a more realistic fashion [Moss, Downing and Pahl-Wostl, 2001]. Agents, in this context, are autonomous software systems that are intended to describe the behaviour of observed social entities (e.g. individuals, organisations, governmental agencies). An enormous advantage of agent based modelling is the ability to assess the plausibility of the behaviour of agents, the ways in which the agents interact and the consequences of that behaviour and interaction. They allow accounting for scaling issues. It is widely recognized that most global change phenomena result from the cumulative effect of numerous activities at regional and local scales. At any scale, decisions are actually taken by individuals or as a result of interactions among groups of individuals. Individuals weigh up the evidence of both their own perceptions and information provided by others. This implies a very different decision making process than was presumed in earlier integrated assessment models. These issues can be captured with agent based modelling techniques and participatory model building processes where decision making is perceived as a process of social learning. Social learning implies the development of a shared problem perception and an understanding for the complexity of the system under consideration, the recognition of different mental frames, the identification of new rules and strategies. In such a context models have a new role and become part of a process of social learning.

The role of information and information tools in government policy more generally has already been discussed for years, but many questions still remain. This is even truer if we zoom in on the role of information in resources management. The gap between model outcomes and resource management practice has been recognised for years, but there has been little success in bridging the gap. Too often information is seen as objective input into decision-making, ignoring issues such as uncertainty and implicit policy choices. Rarely is information and are information tools seen as a means to promote and inform discussions between stakeholders and thus foster social learning. However, it is thus processes of social learning, the development of a shared problem perception, the evolution of shared strategies and perceptions that are crucial for the development of enduring and sustainable resource management regimes. Agent based modelling may both help to improve the representation of the dynamics of social processes in integrated models and to improve the conceptual understanding of

processes of social learning and a new role for models as part of a learning process in stakeholder groups. These arguments are now developed step by step by providing first a brief account of the state of agent based modelling and it's potential for an improved representation of social processes.

## 2. AGENT BASED MODELLING IN A NUTSHELL

Agent based modelling (ABM) allows to capture the behaviour of human beings in a more realistic fashion. An enormous advantage of ABM is the ability to assess the plausibility of the behaviour of agents, the ways in which the agents interact and the consequences of that behaviour and interaction. It is important to emphasize that ABM comprises a wide range of approaches and activities. These range from spatial models with simple rule based cellular automata to complex cognitive architectures of individual agents such as the BDI framework.



**Figure 1:** Abstract space for the three dimensions of complexity for an agent based model.

One may identify the three dimensions of complexity for an agent based model outlined in Fig. 1. Any modeller who intends to develop an agent based model for a particular resource management problem is thus faced with choices regarding:

Agent complexity - numerous approaches exist how to represent the reasoning processes of agents. They may be based on psychological theories (e.g. ACTR or SOAR), on microeconomics - rational actor paradigm and modifications thereof based on bounded rationality, complex cognitive agents architectures or simple heuristics and rule based behaviour. Any approach deviating from the simplicity of the rational actor paradigm of economics results soon in quite complex models [e.g. Jager et al, 2000]. Many conceptual theories on human behaviour have never made it to the stage of being included in a simulation model at all.

Hence making here a choice for a specific implementation of an agent based model is not a trivial issue.

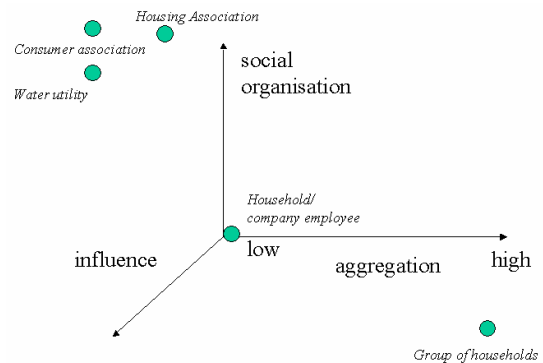
Functional heterogeneity - what type of functional groups should be included in a model. Economists prefer to work with the representative agent approach where a whole collective of diverse agents is represented by one average type. However, what are the effects of neglecting the diversity of agent heterogeneity, e.g. different consumer groups? Such groups may be for example be based on life-style attributes [Kottonau and Pahl-Wostl, in review] or on different cultural perspectives [Janssen and Vries, 1998].

Social network - the interaction among agents is of paramount importance for the diffusion of information or behaviour. In the case of the ideal market, information transfer (via price) is immediate, central and without costs. In the real world, interactions are local, information transfer and processing is associated with costs and takes time. Networks have structure - spatial (e.g. neighbourhood in geometrical space) and social (different types of relationships, friendship groups). Often interactions are based on distributing agents on a rectangular grid. However, investigation of voter behaviour showed that the network structure based on social interactions was of major influence for simulation results [Kottonau and Pahl-Wostl, in press]. The existence of such issues is in general acknowledged, the view on their importance and how to account for them differs largely.

The choice of the appropriate agent based model depends on the goal of the modelling approach and on the complexity of the tasks the agents have to accomplish in their environment. Obviously there is a trade-off between modelling complex interactions in heterogeneous social networks and representing the complexity of the internal reasoning processes of individual agents. Up to now these two fields have developed rather independently. Either researchers have been more interested in the emergence of patterns in complex, spatial networks or they have explored in more detail complex cognitive architectures for individual agents. It will be important to foster an intense exchange between these fields to explore the importance of scale, agent representation and aggregation.

One question that should be resolved in such exchanges is for example the appropriate representation of individual and collective agents in spatial settings. Can a representation derived from the cognitive base of an individual be easily transferred to a collective agent and even more so to an aggregated group of agents? Economics assumes utility maximizing behaviour for all agents at any scale whether referring to the individual

decision maker, the representative household or the profit maximizing firm. A richer framework for the representation of decision making processes at different levels of aggregation and more investigations into the effect of aggregation are urgently needed. Figure 2 show important dimensions that ought to be considered when aggregating agent behaviour.



**Figure 2** Different levels of aggregation affecting the spatial sphere of influence in an agent based model. "Collective agents" might be associations of companies that comprise a defined communication structure and decision making processes to come to a collective opinion/goal. For aggregations of agents such as a group of households / farms the situation is different. Here the aggregation implies that the properties of individual households can be represented by an aggregated average. This is an entirely different process of aggregation.

Hence it must be emphasized that considerable uncertainty is inherent in the simulation of any social system. Hare and Pahl-Wostl [2001] investigated the influence of the choice of different types of agent rationality on the outcome of policy options in quite a simple system - nitrate pollution by farming agents. They discovered that the structural model uncertainty inherent in the choice of agent rationality far outweighed any uncertainty deriving from parameter uncertainties or stochastic effects coming e.g. from climate. Uncertainty based on the choice of agent rationality should be explored in a more systematic fashion.

The reasons for uncertainty inherent in any simulation of social systems are manifold. Firstly, a sound theoretical base for representing human systems in an integrated fashion is lacking. And secondly, the predictability of human behavior can be questioned in principle. Molecules follow the laws of nature and a river will not reverse its direction if faced with new information about its state. Human beings, however, may change the rules under which they operate; they may engage in a collective choice process and change their strategies within the constraints of the material

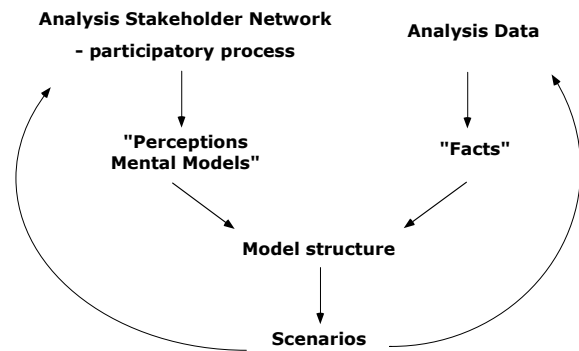
boundary conditions. This implies a self-reference that puts any traditional approaches to systems analysis into question. The analyst and the model become part of a process. Hence, social simulation practitioners see model building and scenarios as a route to build a dialogue and a means for a co-production of knowledge rather than a means to develop predictive forecasts. The role of a model may be to provide the base for plausible scenarios and finally decisions are made in a process of social learning. This is reflected in the approach of participatory agent based social simulation

### 3. PARTICIPATORY AGENT BASED SOCIAL SIMULATION

Participatory agent based social simulation deviates in a number of ways from conventional modeling. The actors themselves whose behavior is represented in the model and who are supposed to later use the models for decision making and strategic planning, participate and contribute to the modeling process. This guarantees that the model captures issues that are of relevance to the actors involved. And the model captures their subjective perceptions and expectations. In any investigation of a system there exist objective components and subjective elements. Decision making is shaped by the perspectives of the decision makers involved. Decision makers have subjective mental models on how the system functions. They base their decisions on their subjective understanding of the world [DeGeus, 1992; Pahl-Wostl, 1995]. They have an implicit knowledge about the formal, and in particular the informal rules governing the decision making processes. Hence, any systems analysis for problem solving has to encompass the human dimension explicitly.

Figure 3 shows the two major streams that inform the agent based model - the data from the analysis and the subjective perceptions derived from the participatory process.

In general, approaches to systems analysis in the natural sciences perceive models as a means to capture the processes governing systems behavior. A good model is judged by its ability to simulate phenomena observed in the real world and to make testable predictions about system behavior. Figure 3 emphasizes that an important role of models in processes of social learning is to bridge the gap between the "external" descriptions of a system as derived from the analyst and the "internal" mental models of the system on which stakeholder base their decisions. Model serves processes of learning rather than predictive purposes (Lane, 1992; Pahl-Wostl, 1995).



**Figure 3** Combination of "hard" and "soft" systems methodologies for analyzing stakeholder networks and for participatory model development and application. The development of the model is informed both by methods of analyzing data and developing systems categorizations based on abstract notions and by the elicitation of mental models and subjective categories derived from individual stakeholders.

In processes of social learning two types of mental models are of major interests

1. Assumptions about cause effect relationships in the overall system crucial for the interpretation of the past, orientation in the presence and for estimating the effects of future actions.
2. Perceptions of the stakeholder network and expectations about other agents behaviour crucial for developing collective strategies and for evaluating the consequences of individual actions.

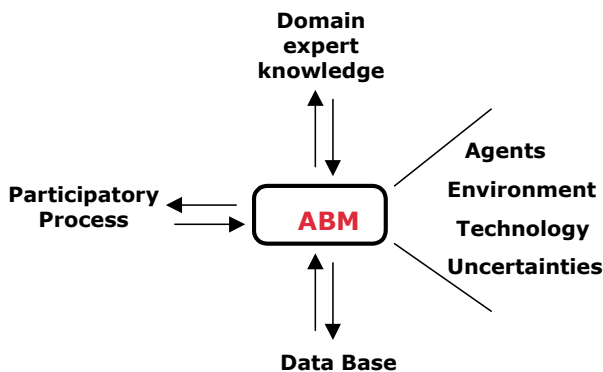
Currently new approaches from artificial intelligence are explored in the FIRMA project to elicit this type of knowledge and to explore how it affects decision making processes in water supply management [Hare and Pahl-Wostl in press].

The methodology integrates methods for knowledge elicitation and group learning from management science, clinical psychology and knowledge engineering. Agent-based models are developed in different media in order for the stakeholders to have different levels of involvement with the models, depending on the need for them to learn about each other's perspectives or to assess a range of possible management scenarios. It allows combining "subjective" knowledge elicited from the stakeholders with "objective" knowledge derived from data. This integration is facilitated by combining a role playing approach with the development of an agent based computer model. The combination of role playing and agent based models has successfully been explored in a number of resource management problems [e.g. Barreteau et al, 2001]. It seems to be a particularly

efficient approach to foster processes of social learning.

#### 4. ROLE OF MODELS AND DIMENSIONS OF VALIDATION

An agent based model in participatory agent based social simulation is informed by different processes and hence has to be validated against these different purposes. This is summarized in Fig. 4.



**Figure 4.** Different dimensions in the process of developing and validating an agent based model (ABM).

These dimensions are briefly discussed and illustrated from a participatory process and agent based model in the context of developing new strategies for water supply management [Tillman et al, 2001, Hare et al, in press, Pahl-Wostl in press].

1. Data base and coherence with observed factual knowledge.

Any model has an input from factual knowledge as derived from data such as long term monitoring, statistical surveys of consumer behaviour, data on water demand and pricing regimes. The outputs produced from simulation runs can be validated against their ability to reproduce empirical patterns.

2. Subjective expert opinion

In this case subjective expert knowledge was used to elicit the rules the govern decision making processes and management strategies in water supply management. These rules were implemented into a model and validated against how they could reproduce behaviour in system variables such as total capacity as derived from empirical data and against their plausibility in the assessment of the expert peer group.

3. Input from and the model's role to facilitate a process of social learning.

On the base of previous investigations an extended participatory process was designed where an agent based model in combination with a role playing exercise is currently used to explore processes of

social learning and the development of new strategies in a stakeholder group.

Such a stepwise and iterative process allows to combine factual knowledge as derived from empirical data, subjective expert knowledge about decision making rules, and mental models about system behaviour and social structure. This combination is a prerequisite to engage successfully in a process of social learning where attention is paid to issues such as the development of shared problem definition and shared understanding of the socio-technical and physical system at stake, perception issues and mental frames, negotiation processes and strategies, and the quality of communication.

Whereas traditional validation techniques for judging a model in its ability to reproduce empirical observations are well established more work should be devoted to develop techniques that allow to assess the performance of a model in its ability to foster and facilitate processes of social learning

#### 5. CONCLUSIONS

Agent modelling, in general and participatory agent based social simulation, in particular, have a great potential for improving the representation of the human dimension in both integrated assessment models and integrated assessment processes. One can thus expect that they will play an important role in resources management in general. The experience up to now is limited and too early to already judge if the agent based approach has fulfilled the expectation it raised [for reviews of the current state of applications see e.g. Ferrand, N., 1999 or Hare, Deadman et al, 2001]. The current paper summarized briefly a number of conceptual issues that should be addressed to improve the application of agent based models in resources management and to lay the foundations for a systematic and comparative approach. In particular, it was also emphasized that agent based modelling is more than simply a new technique to represent social processes in integrated assessment models. It paves as well the way for thinking about a new role of models in processes of social learning.

On the way to a systematic approach a number of major research questions and challenges have to be tackled:

How to represent social processes and make a choice along the three dimensions outlined in Fig.1? Should the representation be theory driven or driven by a more pragmatic empirical approach? How should one combine insights and concepts from different disciplines (economics, psychology, sociology etc)? The problem is the lack of a comprehensive theoretical framework for

representing human systems in a multi-disciplinary context. Contrasting with ecosystem science where a common modelling framework exists this has not yet been accomplished for the human side. Actor based analysis and modelling might lay the foundations for such a framework.

Linking modelling and participation - how to improve the process of knowledge elicitation and model building?

Processes of social learning - how to define processes of social learning and how to use participatory agent based social simulation to promote them.

Scale - how to aggregate agent based models across scales?

Dimensions of validation - how can we make sure that the models and approaches chosen fulfil the purposes they are designed for?

Linking an ecosystem approach with actor based analysis and modelling processes taking into account the mental frames and subjective perceptions of the actors involved seems to be a very promising approach to bridge the gap between the natural and the social sciences as well as to bridge the gap between science and policy.

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