Applications of Agent Based Simulation

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Abstract. This paper provides a survey and analysis of applications of Agent Based Simulation (ABS). A framework for describing and assessing the applications is presented and systematically applied. A general conclusion from the study is that even if ABS seems a promising approach to many problems involving simulation of complex systems of interacting entities, it seems as the full potential of the agent concept and previous research and development within ABS often is not utilized. We illustrate this by providing some concrete examples. Another conclusion is that important information of the applications, in particular concerning the implementation of the simulator, was missing in many papers. As an attempt to encourage improvements we provide some guidelines for writing ABS application papers.

1 Introduction

The research area of Agent Based Simulation (ABS) continues to produce techniques, tools, and methods. In addition, a large number of *applications* of ABS have been developed. By ABS application we here mean actual computer simulations based on agent-based modelling of a real (or imagined) system in order to solve a concrete problem. The aim of this paper is to present a consistent view of ABS applications (as they are described in the papers) and to identify trends, similarities and differences, as well as issues that may need further investigation.

As several hundreds of ABS applications have been reported in different publications, we had to make a sample of these. After having performed a preliminary search for papers describing ABS applications that resulted in about 50 papers, we identified one publication that was dominating. About 30% of the papers were published in the post-proceedings of the MABS workshop series [1, 2, 3, 4, 5] whereas the next most frequent publications covered only 10%. We then chose to focus on the MABS publication series and found 28 papers containing ABS applications (out of 73). Even if we cannot guarantee that this is an unbiased sample, we think that selecting all the applications reported in a particular publication series with a general ABS focus (rather than specializing in particular domains etc.), is at least an attempt to achieve this.

In the next section, we present the framework that will be used to classify and assess the applications. This is followed by a systematic survey of the sampled papers. Finally, we analyze our findings and present some conclusions.

L. Antunes and K. Takadama (Eds.): MABS 2006, LNAI 4442, pp. 15–27, 2007.

2 Evaluation Framework

An ABS application models and simulates some real system that consists of a set of entities. The ABS itself can be seen as a multi-agent system composed of a set of (software) agents. That is, there is a correspondance between the real system and the multi-agent system as well as between the (real) entities and the agents. We will use the terms "system" and "entity" when referring to reality and "multi-agent system" and "agent" when referring to simulation models. For each paper we describe different aspects of the problem studied, the modeling approach taken to solve it, the implementation of the simulator, and how the results are assessed.

2.1 Problem Description

Each problem description includes the domain studied, the intended end-user, and the purpose of the ABS application.

Domain: The domain of an application refers to the type of system being simulated. We identified the following domains after analyzing the sampled papers:

1) An *animal society* consists of a number of interacting animals, such as an ant colony or a colony of birds. The purpose of a simulation could be to better understand the individual behaviors that cause emergent phenomena, e.g., the behavior of flocks of birds.
2) A *physiological system* consists of functional organs integrated and co-operatively related in living organisms, e.g., subsystems of the human body . The purpose could be to verify theories, e.g., the regulation of the glucose-insulin metabolism inside the human body.
3) A *social system* consists of a set of human individuals with individual goals, i.e., the goal of different individuals may be conflicting. An example could be to study how social structures like segregation evolve.
4) An *organization* is here defined as a structure of persons related to each other in purposefully accomplishing work or some other kind of activity, i.e., the persons of the organization have common goals. The aim of a simulation could be to evaluate different approaches to scheduling work tasks with the purpose of speeding up the completion of business processes.
5) An *economic system* is an organized structure in which actors (individuals, groups, or enterprises) are trading goods or services on a market. The applications which we consider under this domain may be used to analyze the interactions and activities of entities in the system to help understand how the market or economy evolves over time and how the participants of the system react to the changing economic policies of the environment where the system is operating.
6) In an *ecological system* animals and/or plants are living and developing together in a relationship to each other and in dependence of the environment. The purpose could be to estimate the effects of a plant disease incursion in an agricultural region.
7) A *physical system* is a collection of passive entities following only physical laws. For example, a pile of sand and the purpose of the simulation may be to calculate

the static equilibrium of a pile considering forces between beads and properties within the pile considered as a unit.

8) A *robotic system* consists of one or more electro-mechanical entities having sensory, decision, tactile and rotary capabilities. An example is the use of a set of robots in patrolling tasks. The purpose of the simulation could be to study the effectiveness of a given patrolling strategy.
9) *Transportation & traffic systems* concern the movement of people, goods or information in a transportation infrastructure such as a road network or a telecommunication network. A typical example is a set of interacting drivers in a road network. The purpose of a simulation could be to create realistic models of human drivers to be used in a driving simulator.

End-users: The end-users of an ABS application are the intended users of the simulator. We distinguish here between four types of end-users: *scientists*, who use the ABS in the research process to gain new knowledge, *policy makers*, who use ABS for making strategic decisions, *managers* (of a systems), who use ABS to make operational decisions, and *other professionals*, such as architects, who use ABS in their daily work.

Purpose: The purpose of the studied ABS applications is classified according to *prediction, verification, training* and *analysis.* We refer to prediction as making prognoses concerning future states. Verification concerns the purposes of determining whether a theory, model, hypothesis, or software is correct. Analysis refers to the purpose of gaining deeper knowledge and understanding of a certain domain, i.e., there is no specific theory, model etc to be verified but we want to study different phenomena, which may however lead to theory refinement. Finally, training is for the purpose of improving a person's skills in a certain domain.

2.2 Modeling Approach

The modeling aspects are captured by the eight aspects described below.

Simulated Entities: They are the entities distinguished as the key constituents of the studied systems and modeled as agents. Four different categories of entities are identified: *Living thing* - humans or animals, *Physical entity* - artifacts, like a machine or a robot, or natural objects, *Software process* - executing program code, or *Organization* - an enterprise, a group of persons, and other entities composed by a set of individuals.

Number of Agent Types: Depending on the nature of the studied application, the investigators have used one or more different agent types to model the distinct entities of the domain.

Communication: The entities can have some or no interaction with one another. The interactions take place in the form of inter-agent communication, i.e., messaging. Here, we defined two values to indicate whether communication between agents exists or not.

Spatial Explicitness refers to the assumption of a location in the physical space for the simulated entities. This can be expressed either as absolute distance or relative positions between entities.

Mobility refers to the ability of an entity to change position in the physical space. Although the real world entities may be spatially situated or moving from place to place, this fact need not be considered in the simulation if its inclusion or omission does not affect the outcome of the study.

Adaptivity is the ability of the entities to learn and improve with experience that they may acquire through their lifetime. Two values are defined to indicate whether the simulated entities are adaptive or not.

The structure of MAS refers to the arrangement of agents and their interaction in the modeled system to carry out their objectives. This arrangement could be in one of the following three forms: peer-to-peer, hierarchical, or recursive. In a peer-to-peer arrangement, individual entities of the modeled system are potentially interacting with all other entities. In a hierarchical structure, agents are arranged in a tree-like structure where there is a central entity that interacts with a number of other entities which are located one level down in the hierarchy. Whereas, in a recursive structure, entities are arranged in groups, where the organization of each group could be in either of the forms above, and these groups are interacting among each other to accomplish their tasks. The three types of MAS structure are illustrated in Fig 1.

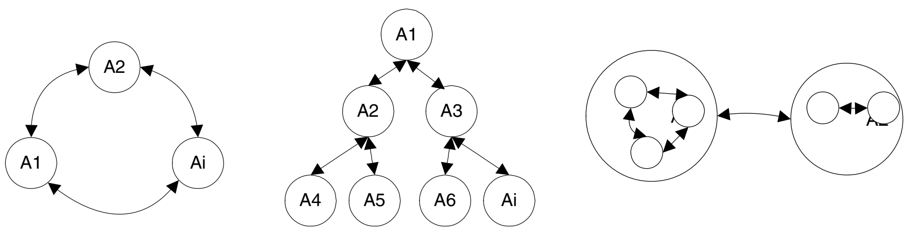

Fig. 1. Peer-to-peer, hierarchical, and recursive organization of a MAS

Dynamic: If the modeled entities are able to come into existence at different instances of time during a simulation, we regard them as *dynamic*.

2.3 Implementation Approach

The implementation approach used is described in terms of the following aspects:

Platform used: The software platform is the development environment, tool or language with which the ABS application is developed. The platforms provide support to different degrees for the developers so that they need not worry about every implementation detail.

Simulation size describes the number of agents participating in the implementation of the ABS application. If the number is different between simulations or is changing dynamically during a simulation, we will use the largest number.

Scale: The size of data used in the actual simulations has been divided into *limited/partial* or *full-scale* data. The full-scale data represents data for a whole system, while the limited/partial data only covers parts of the system.

Input data: The data used in the experiment can either be *real data*, i.e. taken from existing systems in the real world, or data that is not real, i.e. *artificial*, synthetic or generated.

Distributed: ABS applications, depending on the size and sometimes the nature of the application, may require different execution environments: a single computer, if the number is small or several computers in a distributed environment, if the number of agents is large.

Mobile agents: Agents executing in a distributed environment can be described by their mobility, as static or mobile. Static agents run on a singular computer during their lifetime. Mobile agents, on the other hand, are able to migrate between computers in a network environment.

2.4 Results

The classification of the result of the approaches will be in terms of maturity of the research, comparison to other approaches and the validation performed.

Maturity: ABS applications can have varying degree of maturity. In our framework the lowest degree of maturity is *conceptual proposal*. Here the idea or the principles of a proposed application is described, but there is no implemented simulator. The next level in the classification is *laboratory experiments* where the application has been tested in a laboratory environment. The final level, *deployed system*, indicates that the ABS system actually is or has been used by the intended end-users, e.g., traffic managers that use a simulator for deciding how to redirect the traffic when an accident has occurred. If the authors of the paper belong to the intended end-users (researchers), we classify the application as deployed if the authors draw actual conclusions from the simulation results regarding the system that is simulated (rather than just stating that ABS seems appropriate).

Evaluation comparison: If a new approach is developed to solve a problem which has been solved previously using other approaches, the new approach should be compared to existing approaches. That is, answer the question whether ABS actually is an appropriate approach to solve the problem. Such an evaluation could be either qualitative, by comparing the characteristics of the approaches, or quantitative, by different types of experiments.

Validation: In order to confirm that an ABS correctly models the real system it needs to be validated. This can be performed in different ways, *qualitatively*, e.g., by letting domain experts examine the simulation model, or *quantitatively*, e.g., by comparing the output produced by the simulator with actual measurements on the real system.

3 Results

In table 1 the framework is summarized. Table 2 shows how the papers were classified according to the framework. If a paper does not explicitly state to which category the simulator belongs but there are good reasons to believe that it belongs to a particular category, it is marked by an asterisk (*). If we have not managed to make an educated guess, it is marked by “-“.

Table 1. Summary of the framework

	Aspect	Categories
Problem description	Domain	1. Animal societies 2. Physiological systems 3. Social systems 4. Organizations 5. Economic systems 6. Ecological systems 7. Physical systems 8. Robotic systems 9. Transport/traffic systems
	End-user	1. Scientists 2. Policy makers 3. Managers 4. Other professionals
	Purpose	1. Prediction 2. Verification 3. Analysis 4. Training
Modeling approach	Simulated entity	1. Living 2. Physical artefact 3. Software process 4. Organisation
	Agent types	1 - 1.000
	Communication	1. no 2. yes
	Spatial explicitness	1. no 2. yes
	Mobility	1. no 2. yes
	Adaptivity	1. no 2. yes
	Structure (of MAS)	1. Peer-to-peer 2. Hierachical 3. Recursive
	Dynamic	1. no 2. yes
Implementation approach	Platform used	NetLogo, RePast, Swarm, JADE, C++, etc.
	Simulation size	1 - 10.000.000
	Scale	1. Limited/partial 2. Full-scale
	Input data	1. Artificial data 2. Real data
	Distributed	1. no 2. yes
	Mobile agents	1. no 2. yes
Results	Maturity	1. Conceptual proposal 2. Laboratory experiment 3. Deployed
	Evaluation	1. None 2. Qualitative 3. Quantitative
	Validation	1. None 2. Qualitative 3. Quantitative

Table 2. The classification of the studied papers

Paper	Problem			Modeling								Implementation						Results		
	Domain	End-user	Purpose	Sim. Entity	N.o. types	Commun.	Spatial	Mobile	Adaptive	MAS str.	Dynamic	Platform	Size	Scale	Input data	Distributed	Mobile	Maturity	Evaluation	Validation
[6]	4	3	1	3	2	2	1	1	1	2*	1	C++	10	1	1	1*	1*	2	1	1
[7]	4	3,4	3	1	-	2	2	-	2	-	-	-	-	-	-	-	-	1	1	1
[8]	4	1,2	1,3	1	4	1	1	1	1*	1*	1	-	-	1	2	1*	1*	3	1	3*
[9]	4	1,2	3	1,4	2	1	1	1	1	2*	1	RePast	60	1	1	1*	1*	3	1	1
[10]	9	1,2	1	2	-	1	2	2	1	-	1	-	120	2	1	-	-	3	1	1
[11]	3	1	3	1	1	1	2	1	1	1	1	-	100	1	1	1*	1*	3	1	2*
[12]	3,9	1	2	1,2	3	2	2	2	1	1	2	-	12000	2	2	2*	2*	2	1	1
[13]	4	1,4	3	1	2	2	2	2	2	1	2	WEA	25*	2	2	2*	2*	2	1	3
[14]	9	3	2	1	1	1	2	2	1*	1	1*	-	100*	1	1	1*	1*	2	2	3
[15]	3,6	1	3	1	3	1*	2	2	2*	1	2	Swarm	540	1	1	1*	1*	3	1	1
[16]	5,9	2	3	1	6	2	1	1	1	2	1	Jade	7	1	2	1*	1*	2	1	1
[17]	7	1	3	2	1	2	2	1	1	1	1*	-	10^6	1	1	1*	1*	2	2,3	2
[18]	5	1	2,3	1,4	3	2	1	1	1*	2	2	-	102	1	1	1*	1*	3	1	2
[19]	3	1,4	2	1	1	1	2	2	1*	1	2	NetLogo	200	1	1	1*	1*	2	2	1
[20]	1	1	3	1	2	1*	2	2	1	1	1	ObjectPascal	8	1	1	1	1	3*	1	3
[21]	3	1	2	1	1	1*	2	2	1	1	1	-	250	1	1	1*	1*	3*	1	1
[22]	2	1	2	2	3	2	1	1	2	3	1	Java	4	2	1*	2*	1*	3	1	3
[23]	3	1	3	1	3	2	1	1	1	1	1	-	9	1	1	1*	1*	2	1	1
[24]	3	1	3	1	1	2	2	2	1	1	2	Sugarscape	700	1	1	1*	1*	3*	1	1
[25]	3,6	2	3	1	3	2	2	2	1	1	1	Cormas	-	1	2	1*	1*	2	1	3
[26]	3	1,2	3	1,3	3	2*	1	1	1	1	2	VisualBasic	10000	1	1	1	1	2	3	1
[27]	4,7	3	3	1,2	5	2	2	2	2	1	1	C++	1	1	1	1	1	2	1	1
[28]	3	1	2,3	1	2	1	1	1	2	1	1	NetLogo	500	1	1	1*	1*	2	2	1
[29]	4	2	3	1,2	3	2	2	2	2	1	1	RePast	61	1	2	1*	1*	3	2	1
[30]	8	1	1,2	2	1	2	2	2	1	1	1	C++	25	1	1	1*	1*	3*	1	1
[31]	5	1	3	1	7	2	1	1	2	2	1	DECAF	3	1	1	1*	1*	2	1	1
[32]	3	2	3	1	1*	2	2	1	2*	1	1	-	-	1	1	1*	1	3*	2	2
[33]	5	1	3	1	1	2	1	1	1	1	1	-	24*	2	1	1*	1*	2	3	1

4 Analysis

4.1 Problem Description

The results indicate that ABS is often used to study systems involving interacting human decision makers, e.g., in social, organizational, economic, traffic and transport systems (see Fig. 2). This is not surprising given the fact that qualities like autonomy, communication, planning, etc., often are presented as characteristic of software agents (as well as of human beings). However, as (some of) these qualities are present also in other living entities, it is interesting to note that there was only one paper on simulating *animal societies* and just two involving *ecological systems*. Very few papers are found on simulating technical systems, such as *ICT systems*, i.e., integrated systems of computers, communication technology, software, data, and the people who manage and use them, *critical infrastructures, power systems etc.*. The aim of such models might be to study and have a deeper understanding of the existing and emerging functionalities of the system and analyze the impact of parameter changes. (The only paper on simulating technical systems concerned robotic systems.)

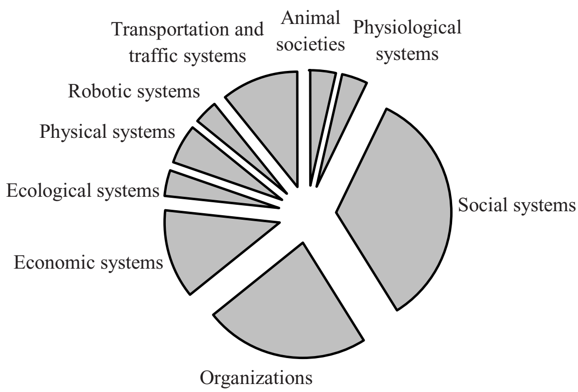

Fig. 2. The distribution of the type of domains simulated

In more than half of the applications, researchers were the intended end-user. As can be seen in Fig 3., the most common purpose of the applications included in the study was analysis. However, no paper reported the use of ABS for training purposes indicating that this may be an underdeveloped area.

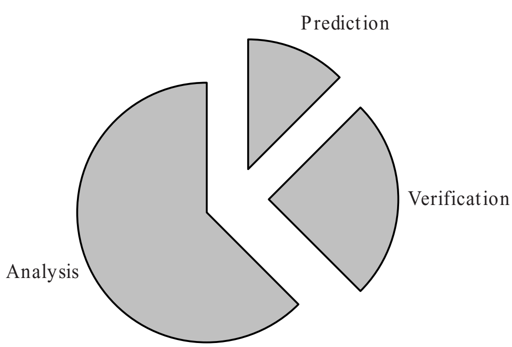

Fig. 3. The distribution of purpose

4.2 Modeling Approach

The simulated entities are mostly living things, indicating that ABS is believed to be better suited to model the complexity of human (and animal) behaviour compared to other techniques. However, it should be noted that in some applications there were entities not modeled and simulated and implemented as agents. Hybrid systems of this kind are motivated by the fact that some entities are passive and are not making any decisions, especially in socio-technical systems. The model design choices for some of the aspects seem to be consequences of the characteristics of the systems simulated. After all, the aim is to mirror the real system. These aspects include number of agent types, only about 15% of the applications had more than three different agent types, spatial explicitness (60% do use it), mobility of entities (50%), communication between entities (64%), and the structure of the MAS where a vast majority used a peer-to-peer structure (77%). However, as illustrated in Fig. 4, there are some modelling aspects where the strengths of the agent approach do not seem to have been explored to its full potential. For instance, only 9 of the 28 papers make use of adaptivity, and just 7 out of the 27 implemented systems seem to use dynamic simulations.

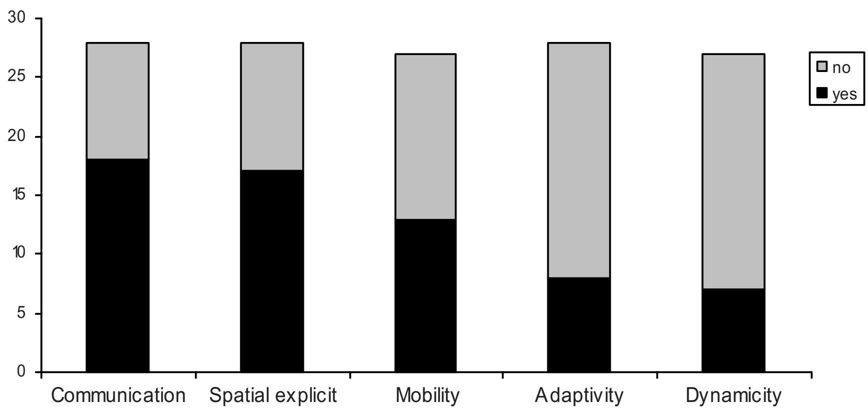

Fig. 4. The distribution of modeling aspects

4.3 Implementation Approach

Nearly half of the papers do not state which software were used to develop the ABS. In particular, it is interesting to note that the two papers with the largest number of agents do not state this. Of the agent platforms and simulation tools available, none is dominantly used. In fact, many of the simulations were implemented with C++ or programs developed from scratch. A possible reason for this may be that many ABS tools and platforms make limiting assumptions regarding the way that entities are modeled. The number of agents in the simulation experiments is typically quite small (see Fig. 5). In 50% of the papers the number of agents were 61 or less. The fact that most simulation experiments were limited covering only a part of the simulated system, may be an explanation for this. The reasons for this are seldom discussed in the papers but are probably lack of computing hardware, software (such as proper agent simulation platforms), or the time available to perform the experiments. Moreover, there may be a "trade-off" between the complexity of the agents and the number of agents in the experiments, i.e., that large sized simulations use relatively simple agents whereas smaller simulations use more complex agents. However, further analysis is necessary before any conclusions can be drawn.

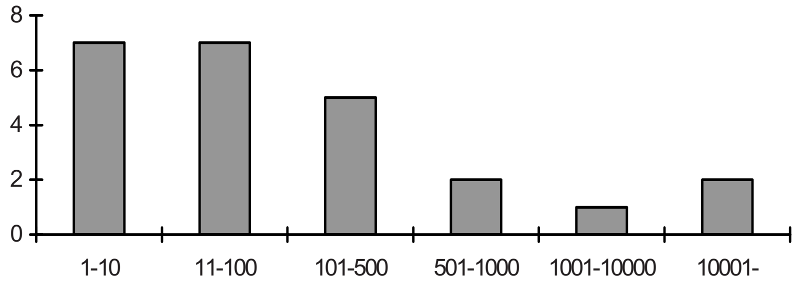

Fig. 5. The frequency of different simulation sizes (number of agents)

Many of the simulation experiments are conducted with artificial data, typically making simplifying assumptions. This is often due to reasons beyond the researchers' control, such as availability of data. As a consequence, it may be difficult to assess the relevance of the findings of such simulations to the real world problems they aim to solve. It seems as very few of the simulators are distributed, and no one is using mobile agents. However, these issues are seldom described in the papers.

4.4 Results

We have not encountered any ABS applications that are reported to be deployed to solve actual real world operational tasks. The examples of deployed systems are limited to the cases where the researchers themselves are the end-users. The cause of this could be the fact that ABS is a quite new methodology, or that the deployment phase

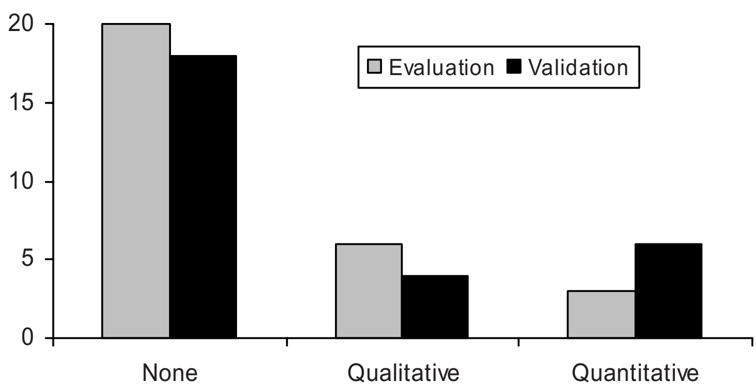

Fig. 6. The frequency of different types and evaluation

often is not described in scientific publications. As illustrated in Fig. 6, less than half of the simulations are actually reported to be validated. This is particularly striking as it is in most cases the complex behaviors of humans that are being simulated. Also, comparisons to other approaches are very rare.

4.5 Limitations of the Study

Although the conclusions drawn from our study are valid for the work published in the MABS proceedings, a larger sample is probably needed to verify that they hold for the whole ABS area. There were a number of interesting aspects that we were not able to include in our study. For example, regarding the problem description, the *size* of the actual problem, i.e., the system being simulated would be interesting to know. Typically, only a partial simulation is made, i.e., the number of entities in the real system is much larger than the number of agents in the simulation. However, in most papers the size of the real system is not described and often it was very difficult for us to estimate the size. Another interesting aspect not included in this study is the modeling of entities. The representation of the behavior and state of the real world entities should be sufficiently sophisticated to capture the aspects relevant for the problem studied. We initially categorized the ways of modeling the entities in the following categories: Mathematical models; Cellular automata; Rule-based (a set of explicit rules describe the behavior of the agent); Deliberative (the behavior is determined by some kind of reasoning such as planning). Unfortunately, there were often not enough information in the papers concerning this aspect. Related to this is the distinction between proactive versus reactive modeling of entities, which also was very difficult to extract from the papers due to lack of information. Regarding the implementation, we wanted to investigate how the agent models were implemented in the simulation software. We found examples ranging from simple feature vectors (as used in traditional dynamic micro simulation) to sophisticated software entities corresponding to separate threads or processes. However, also in this case important information was often left out from the presentation.

5 Conclusions

The applications reviewed in this study suggest that ABS seems a promising approach to many problems involving simulating complex systems of interacting entities. However, it seems as the full potential of the agent concept often is not utilized, for instance, with respect to adaptivity and dynamicity. Also, existing ABS tools and platforms are seldom used and instead the simulation software is developed from scratch using an ordinary programming language. There may be many reasons for this, e.g., that they are difficult to use and adopt to the problem studied, or that the awareness of the existence of these tools and platforms is limited.

Something that made this study difficult was that important information, especially concerning the implementation of the simulator, was missing in many papers. This makes it harder to reproduce the experiments and to build upon the results in further advancing the state-of-the-art of ABS. A positive effect of our study would be if researchers became more explicit and clear about how they have dealt with the different aspects that we have used in the analysis. Therefore, we suggest the following checklist for ABS application papers:

1. Clearly describe the purpose of the application and the intended end-users.
2. Indicate the typical size of the system (that is simulated) in terms of entities corresponding to agents.
3. For each agent type in the simulation model, describe
    a. what kind of entities it is simulating,
    b. how they are modelled (mathematical, rule-based, deliberative, etc.),
    c. whether they are proactive or not,
    d. whether they are communicating with other agents or not,
    e. whether they are given a spatial position, and if so, whether they are mobile
    f. whether they are capable of learning or not.
4. Describe the structure of the collection of agents, and state whether this collection is static or agents can be added/removed during a simulation.
5. State which simulation (or agent) platform was used, or in the case the simulator was implemented from scratch, what programming language was used.
6. State the size of the simulation in terms of number of agents.
7. Describe how the agents were implemented; feature vectors, mobile agents, or something in-between.
8. State whether the simulator actually has been used by the intended end-users, or just in laboratory experiments. In the latter case indicate whether artificial or real data was used.
9. Describe how the simulator has been validated.
10. Describe if and how the suggested approach has been compared to other approaches.

Future work includes extending the study using a larger sample, e.g., include other relevant workshops and conferences, such as Agent-Based Simulation, and journals such as JASSS, in order to reduce any bias. Another interesting study would be to make a comparative study with more traditional simulation techniques including aspects such as size, validation, etc.

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