Trends in the Application of Agent-Based Modeling and Simulation

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***Abstract**. Agent-based modeling and simulation (ABMS) have been used in various fields of science with growing interest. After introduction to the approach, thought-provoking bibliometric data on ABMS usage in numerous fields is presented, including a citation network analysis. We have analyzed almost 3000 papers from Thomson Reuters Web of Science (Science Citation Index Expanded and Social Sciences Citation Index) databases in terms of publishing frequency in the observed journals for the period 2000-2015 and in terms of trends in keywords usage and field of application for the period 2010-2015.*

Keywords. agent-based model, agent-based simulation, application review, bibliometrics, literature review

1 Introduction

Agent-based models (ABM) consist of a set of elements (agents) characterized by specific attributes, which interact with each other following the appropriately defined rules in a given environment. ABMS can be used to reproduce systems related to economy (Cavoski & Markovic, 2015; Marković, Čavoški, & Novović, 2016; Shafiei et al., 2012), ecology (Gerst et al., 2013), agriculture (Rebaudo & Dangles, 2013), medicine (Kasaie, Andrews, Kelton, & Dowdy, 2014), to solve optimization problems (Nikolopoulou & Ierapetritou, 2012), and many others. The usage of ABMS can help in identifying properties and patterns concerning the whole scenario (Billari, Fent, Prskawetz, & Scheffran, 2006) that could not be anticipated nor foreseen by the observation of agents individually due to the complexity of the interactions among the elements of the system (Barbati, Bruno, & Genovese, 2012). Wooldridge and Jennings (1995) defined agent as a computational system interacting with an environment, that can be described with the following features:

- *Independence* - Each agent acts without the direct control of human beings or other devices.
- *Social ability* - Interactions occur among agents through a communication language with the aim to satisfy the objectives.
- *Re-activeness* - Agents answer in a precise way to signals coming from the environment.
- *Pro-activeness* - Agents are capable of acting goal-directed. They take the initiative in order to satisfy their objectives.

Furthermore, it can be concluded from Billari et al. (2006) and Weiss (1999), that the development of an ABM needs a set of basic building blocks to be defined:

- *The object of the simulation* - It has to be specified what is the phenomenon/problem to be reproduced. Also, space, where the simulation takes place, has to be defined.
- *The agents' population* - Agents can be grouped into different categories with common characteristics, reproducing the various components of the reproduced system.
- *The adaptive capability of each agent category* - Agents of each category present a specific adaptive capability, i.e. the degree of reactiveness and pro-activeness.
- *The interaction paradigm among agents* - Each agent can interact with agents of the same or another category. In this context, agents can be competitive if they have conflicting objectives and non-competitive otherwise. In the literature, various interaction paradigms have been defined, which can be mainly classified as *Cooperative paradigms*, when a coordination from among non-competitive agents exists and *Competitive paradigms*, in which some rules for the behavior of competitive agents are defined (Weiss, 1999).

In order to follow their own objectives, agents are interacting and communicating among themselves. Communication capabilities consist of the ability to send and receive messages. This is required to ensure a coordination mechanism among agents, in order to prevent and avoid conflicts among agents' accessing resources or achieving objectives.

Implementing a cooperation-based paradigm means using planning approaches to reduce resource contention and to ensure the achievement of global objectives. No mediator is involved. In this case, each agent is self-interested, meaning that the final solution may be the best for the single agent involved, but not for the group as a whole. These approaches can be distinguished into two main categories (Barbati et al., 2012):

- *Distributed approaches*, in which agents are endowed with self-organizing rules for resource sharing and goal pursuing, and
- *Centralized approaches*, in which a mediator agent is assigned with the task of regulating and supervising agents' behaviors.

Parunak (1999) lists the following characteristics for an ideal application of agent technology:

- *Modular*, in the sense that each entity has a well-defined set of state variables that is distinct from those of its environment and that the interface to the environment can be clearly identified.
- *Decentralized*, in the sense that the application can be decomposed into stand-alone software processes capable of performing useful tasks without continuous direction from some other software process.
- *Changeable*, in the sense that the structure of the application may change quickly and frequently.
- *Ill-structured*, in the sense that all information about the application is not available when the system is being designed.
- *Complex*, in the sense that the system exhibits a large number of different behaviours which may interact in sophisticated ways.

Since its first appearance in early 1970s, the exploration of the ABMS literature has seen vigorous development, especially in the last decade owing to availability of various ABMS software. This paper presents a bibliometric analysis that is geared towards a review of literature productivity and an observation of the trends in ABMS.

After outlining agent-based modeling and simulation more closely, the paper is organized as follows. A bibliometric review of ABMS usage in scientific papers is presented in section 2, including journals and citation analyses, and also research area and keywords trends analyses, all with the goal to raise awareness of ABMS applicability and popularity. Finally, conclusions and some visions for the future research are provided in section 3.

2 ABMS in Literature

In order to analyze the presence of ABMS in the scientific literature we have searched through the Thomson Reuters Web of Science (Thomson Reuters, 2016b) in Science Citation Index Expanded (SCI-EXPANDED) and Social Sciences Citation Index (SSCI) databases and collected data. The keywords we were looking for are: *"agent-based simulation" OR "agent-based model"* for the time interval 2000-2015. The search was conducted for the *topic*, which includes: title, abstract, author and keywords in Web of Science (Thomson Reuters, 2016b).

As displayed in Table 1, we have retrieved data for 2902 papers (Zornic & Markovic, 2016). The increase in the number of papers per year is evident, which means the method is becoming more acknowledged. The number of ABMS-related papers increased almost 30 times from 2000 until 2015, while the total number of SCI-EXPANDED and SSCI papers increased only 1.77 times in the same time period. The biggest leap in ABMS-related published papers occurred in period 2012-2013, from 294 to 380.

Table 1. Number of ABMS-related and total SCI-EXPANDED & SSCI papers

Year	ABMS Papers	Total SCI-EXPANDED & SSCI Papers
2000	15	1,099,828
2001	33	1,087,477
2002	30	1,132,596
2003	61	1,177,644
2004	72	1,272,284
2005	92	1,340,592
2006	116	1,399,016
2007	118	1,471,075
2008	137	1,553,662
2009	173	1,613,263
2010	227	1,650,449
2011	290	1,736,725
2012	294	1,820,086
2013	380	1,917,193
2014	415	1,942,001
2015	449	1,945,858
Total	**2902**	**24,159,749**

2.1 Journals and Citations Analyses

Those 2902 papers are published in 908 journals. In Table 2 we present 19 journals with at least 20 papers published in the observed period (Zornic & Markovic, 2016). The top contributor is the *Journal of Artificial Societies and Social Simulation* with 208 papers published, followed by *Physica A: Statistical Mechanics and its Applications* and *PLoS ONE*. Since its first issue in 1998, *Journal of Artificial Societies and Social Simulation* has been one of the leading references for readers interested in social simulation and the application of computer simulation in the social sciences. The list of journals shows a multidisciplinary interest in ABMS. In addition to journals that are expected to be on the list, journals specialized in Simulation and Modeling (*Journal of Artificial Societies and Social Simulation*, *Simulation Modelling Practice and Theory*, etc.), there are journals specialized in other scientific fields, like: Ecology (*Ecological Modelling*, *Environmental Modelling & Software*, etc.), Biology (*Journal of Theoretical Biology*), Economics (*Journal of Economic Dynamics and Control*, *Journal of Economic Interaction and Coordination*), etc. Table 2 also reports impact factor (IF), IF without journal self-citations, and percentage of change in IF after the self-citations have been excluded. Data about journals and IF is collected from Tomson Reuters InCites™ (Thomson Reuters, 2016a). We can see that the journal with the highest IF is *Environmental Modelling & Software* (4.420), which is also the journal with the highest decrease in IF after the self-citations were excluded (-40.36%). Journal that stands out with high IF (3.234) and a small percentage of change after the self-citations have been excluded (-10.79%) is *PLoS ONE*. We can also see that there are journals with IF lower than 1 (*Environment and Planning B: Planning* and *Design and Advances in Complex Systems*) whose IF did not drastically change after excluding self-citations – the change is lower than 5%.

Table 2. Journals accounting for at least 20 papers

Journal	Papers	Journal IF (2014)	IF Without Journal Self Cites (2014)	% IF Change Without Self Cites
Journal of Artificial Societies and Social Simulation	208	0.941	0.811	-13.82%
Physica A: Statistical Mechanics and its Applications	88	1.732	1.181	-31.81%
PLoS ONE	88	3.234	2.885	-10.79%
Journal of Theoretical Biology	62	2.116	1.868	-11.72%
Ecological Modelling	61	2.321	2.085	-10.17%
Environmental Modelling & Software	49	4.420	2.636	-40.36%
Advances in Complex Systems	45	0.968	0.920	-4.96%
SIMULATION: Transactions of The Society for Modeling and Simulation International	40	0.818	0.631	-22.86%
Simulation Modelling Practice and Theory	33	1.383	1.064	-23.07%
Computers, Environment and Urban Systems	32	1.537	1.349	-12.23%
Computational and Mathematical Organization Theory	24	0.840	0.740	-11.90%
Expert Systems With Applications	24	2.240	1.793	-19.96%
Journal of Economic Dynamics and Control	22	1.018	0.851	-16.40%
Journal of Economic Interaction and Coordination	22	0.962	0.807	-16.11%
Energy Policy	21	2.575	2.106	-18.21%
Physical Review E	21	2.288	1.778	-22.29%
Environment and Planning B: Planning and Design	20	0.983	0.941	-4.27%
Journal of Economic Behavior & Organization	20	1.297	1.154	-11.03%
Journal of Simulation	20	0.580	0.500	-13.79%

Additional analysis of citations is conducted using network visualization and exploration software Gephi (Gephi, 2016). Total citation count for the selected journals has been collected from the Tomson Reuters InCites™ (Thomson Reuters, 2016a) for the period until 2014. The obtained results are displayed in Figure 1 (Zornic & Markovic, 2016), where node size is determined by the percentage of self-citations specific journal has (number self-citations divided by a total number of citations). For example, it is noticeable that *Computers, Environment and Urban Systems* has the lowest (5.56%) and *Environmental Modelling & Software* the highest (20.48%) percentage of self-citations. The weight of the line is defined as the sum of percentages of citations acquired from the other observed journal. For example, *Advances in Complex Systems* got 42 citations from *Physica A: Statistical Mechanics and its Applications* and has 513 citations in total, which means *Advances in Complex Systems* got 8.19% of citations from *Physica A: Statistical Mechanics and its Applications*. In the other direction, *Physica A: Statistical Mechanics and its Applications* got 46 citations from *Advances in Complex Systems* and has 16,974 citations in total, which means *Physica A: Statistical Mechanics and its Applications* got 0.27% of citations from *Advances in Complex Systems.*

The weight of line is determined by the sum of these percentages (8.19% + 0.27%). The size of the arrow is defined separately for each side in a similar manner. For example, the two-sided arrow between

Physical Review E and *Physica A: Statistical Mechanics and its Applications* means that journals have cited each other quite often. Connection between *PLoS ONE* and *Journal of Theoretical Biology* stands out. Namely, *Journal of Theoretical Biology* is very frequently cited by *PLoS ONE* (5.66% of total citations *Journal of Theoretical Biology* received are from *PLoS ONE*). Similarly, we can analyze the remaining connections between journals.

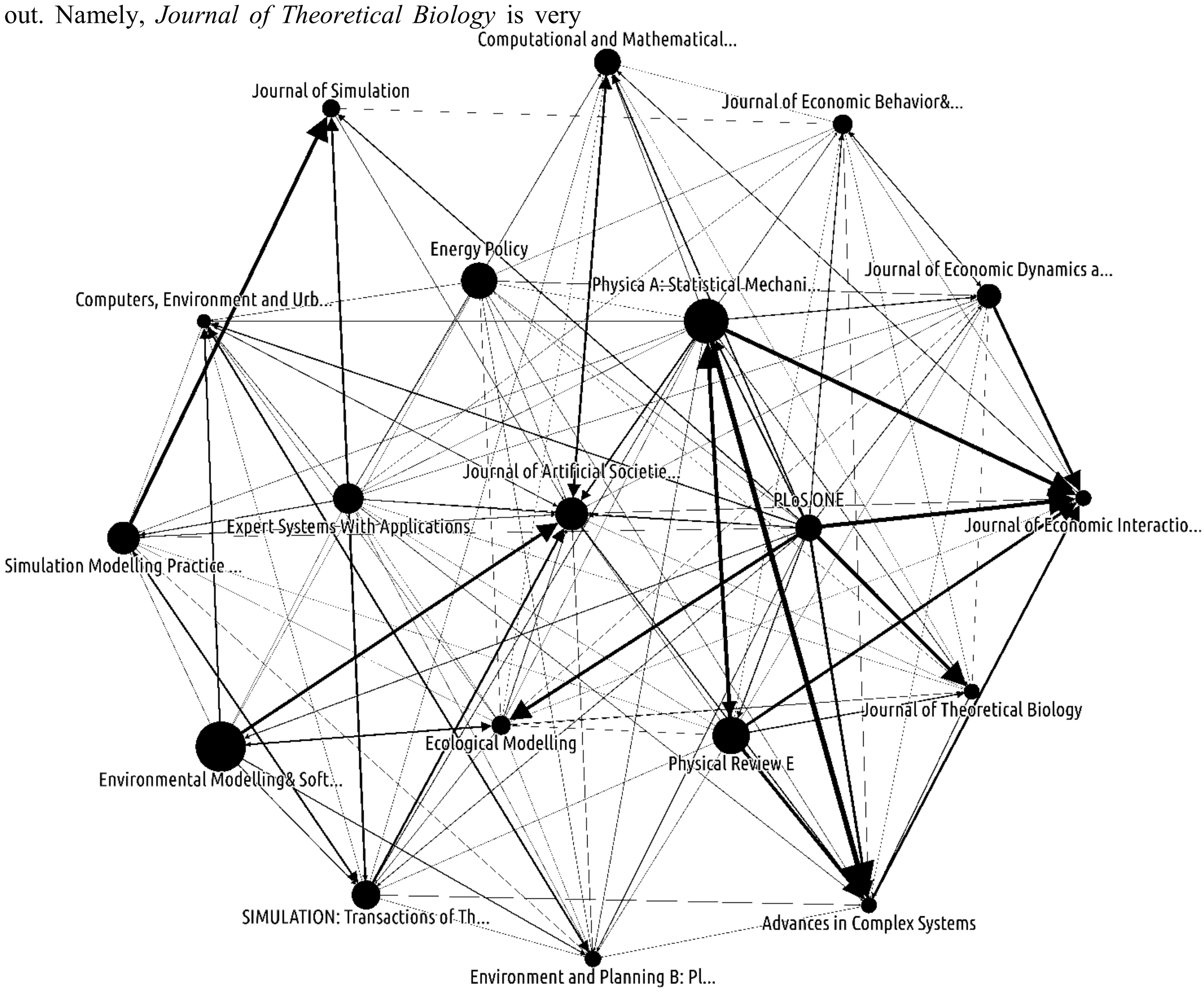

Figure 1. Network of citations among selected journals (Zornic & Markovic, 2016)

2.2 Research Area and Keywords analyses

Analysing the research area in which ABMS are applied we can provide one more evidence that ABMS are suitable for solving various problems (Table 3). Data have been retrieved from Web of Science (Thomson Reuters, 2016b).

We can notice that usage of ABMS in certain research areas is constantly growing. For example, *Environmental Sciences & Ecology* and *Social Sciences - Other Topics*. It is particularly interesting that *Environmental Sciences & Ecology* and *Business & Economics* are among areas with most frequent ABMS usage, just behind IT related areas. We can, also notice a growing interest in ABMS in almost all research areas.

Table 3. Research area trends

Research area	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**Total (2000-2015)**
Computer Science	62	50	65	71	76	80	**635**
Environmental Sciences & Ecology	44	45	51	63	66	66	**441**
Engineering	30	52	44	68	59	67	**396**
Business & Economics	23	38	34	54	50	45	**364**
Social Sciences - Other Topics	19	19	19	23	39	41	**254**
Science & Technology - Other Topics	21	20	25	28	36	47	**219**
Physics	15	21	24	30	26	21	**212**

Research area	2010	2011	2012	2013	2014	2015	Total (2000-2015)
Mathematics	22	18	25	24	27	15	**202**
Operations Research & Management Science	16	15	26	26	22	33	**185**
Mathematical & Computational Biology	15	14	16	25	18	25	**165**
Life Sciences & Biomedicine - Other Topics	15	11	11	16	13	23	**140**
Geography	9	12	13	19	13	13	**101**
Transportation	1	8	11	10	23	19	**86**
Mathematical Methods In Social Sciences	6	10	8	5	5	3	**63**
Public, Environmental & Occupational Health	4	8	4	11	14	12	**63**
Biochemistry & Molecular Biology	5	7	4	9	4	13	**55**
Energy & Fuels	6	5	8	6	7	16	**55**
Sociology	5	11	5	1	8	5	**53**
Information Science & Library Science	5	8	5	10	8	3	**52**
Psychology	6	6	2	4	7	12	**51**

We also placed attention on the keywords authors chose to best represent their work, the most frequent keywords used in the observed papers (Table 4). Disregarding the expected ones (such as *model*, *systems*, *simulation*, etc.), other keywords are describing the field of application (such as *Management*, *Social Networks*, etc.). Keywords with constantly growing usage include *Dynamics*, *Systems*, *Evolution*, etc.

Table 4. Keywords trends

Keyword	2010	2011	2012	2013	2014	2015	Total (2000-2015)
Dynamics	25	35	35	46	58	56	**321**
Model	30	28	33	38	41	58	**301**
Systems	22	23	30	44	41	48	**268**
Simulation	12	20	23	40	42	41	**214**
Behavior	13	25	19	35	39	29	**212**
Management	12	16	18	18	12	26	**141**
Evolution	7	14	10	17	22	23	**138**
Networks	12	19	9	19	29	20	**135**
Models	11	13	8	15	23	20	**123**
Agent-based model	4	8	9	21	20	20	**96**
Cooperation	4	12	8	7	9	13	**79**
Patterns	9	8	5	13	14	11	**79**
Growth	8	7	3	12	13	7	**73**
Land-use	6	10	10	14	10	8	**69**
Design	3	7	12	12	8	9	**67**
Agent-based simulation	2	7	2	10	8	20	**65**
Strategies	8	15	2	7	9	11	**65**
Performance	8	9	10	10	8	10	**63**
Information	5	8	4	5	12	10	**62**
Transmission	5	8	3	7	15	12	**60**

3. Conclusion

In this paper, trends in application of agent-based modeling and simulation are reviewed. Firstly, the comprehensive bibliometric data has been presented, including IF, IF without journal self-citations, and citation network analysis. After that we presented research area and keywords trends analyses.

We can conclude just at a glance that ABMS are successfully used in various fields of science. Moreover, their usage is growing with the course of time, from 15 papers published in 2000, this number increased to 449 in 2015. This proves that researchers from numerous scientific fields recognized the power of ABMS and are utilizing that power for solving the problems they run into.

The growing interest in agent-based modeling and agent-based simulation seems to be a very promising field of study. For this reason, future researches will be devoted to recognize and model other classes of problems using ABMS.

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