A Bibliometric Review of Agent-Based Models in Operations Research

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***Abstract* – Modeling and simulation are used to improve the understanding of a system's behavior, allowing explanatory and predictive capabilities. More specifically, Agent-Based Models are a particular class of computer models for simulating the actions and interactions of autonomous agents within themselves and with an environment. This approach is often used on systems where there are complex relationships and distributed resources. This work presents a bibliometric review of Agent-Based Models (ABM) and Multi-Agent Systems (MAS) in the area of Operations Research. The first part presents a broader view of ABM during the period from 2007 to 2017 for an understanding of the fields where this approach is used. The second part presents a more specific analysis of Agent-Based Models in the area of operations research. The results show that this Agent-Base Models and Multi-Agents Systems are used on a variety of fields, including artificial intelligence and social sciences, and that in Operations Research they are used for a variety of applications including optimization and systems modeling.**

***Keywords* – Agent-Based Model, Multi-Agent System, Operations Research.**

I. INTRODUCTION

Modeling and simulation are useful and contribute to the understanding of the object under study and to the scientific process in the sense that it can represent and test a scientific hypothesis ([1]).

More specifically, Agent-Based Models (ABM) or Multi-Agent Systems (MAS) consist of a series of elements (agents) characterized by attributes that interact with each other through the definition of appropriate rules on a given environment. ABM are used on a variety of applications, such as social sciences, economy ([2]), logistics optimization, biology and urban planning ([3]). ABM are also associated with the simulation of sociotechnical systems where real experiments with different scenarios is not possible to be accomplished.

Such modeling approach is often associated with complex systems, where ABM provide a systemic view to complex problems that could not be decomposed using the traditional Cartesian logic ([4]).

Reference [5] suggests the use of ABM for the identification of novel rare emergent behavior in complex systems. These authors also compare the ABM approach with other simulation paradigms (discrete events and system dynamics) where the earlier can be used on a broader ranges of model abstraction.

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ABM is the theme of a number of bibliographic and bibliometric reviews regarding different aspects of this approach. Reference [2] shows a literature review of agent-based models for optimization problems. Reference [6] shows a bibliometric review of agent-based modeling and proposes a method to identify the main topics of the literature related to ABM. Reference [7] shows a review of the ABM state-of-the-art software.

The current work presents a bibliometric review of ABM and MAS, with a brief overview of this approach in a broader sense and a more detailed view in the field of Operations Research and Management Sciences (ORMS). The focus on ORMS is due to the interest of the authors in understanding the role of ABM in this research area, specially in Behavioral Operations Research and in "Soft" Operations Research, such as Problem Structuring Methods.

II. METHODS AND TOOLS

This section describes the database of the bibliometric review, the terms used for the searches and the metrics utilized to extract information from the articles related to the ABM field and more specifically to ABM in the Operations Research area.

A. Database

The first step to perform the bibliometric review was to choose the database that could provide the data for the analysis. There are several databases available, such as Scopus, Clarivate Analytics Web of Science (WoS), Cochrane Database of Systematics Reviews (Health Care) , PubMed (biomedial literature) and Google Scholar. Due to the availability on the moment of the research and to the great number of indexed articles, the Clarivate Analytics Web of Science was chosen.

Inside the Clarivate Analytics Web of Science, the searches were performed in the Web of Science Core Collection, that has access to more than 20.000 journals and 1.4 billion cited references going back to 1900 ([8]).

The Web of Science Core Collection works with citation indexes that contain the references cited by the authors of the publications covered by the index. This database contains the indexes from sources such as journals, conference proceedings and books ([9])

B. Terms used on the searches

The terms used on the search are "agent-based model*" and "multi-agent system*".

The wildcard "*" was used to cover occurrences of the terms "models" and "modeling" for ABM and "systems" for MAS. The hyphen was used between "agent" and "model" since there were a number of occurrences of articles that contain these terms separately and were out of the scope of ABM, such as health science publications. For the same reason the hyphen between "multi" and "agent" was used.

An "or" condition was used between the topics "agent-based model*" and "multi-agent system*" since these terms are often used as synonyms. Multi-agent system is often found on articles that describe the agents and also the computer system implementation, including aspects such as distributed computing and information exchange protocols.

The search was also filtered by document type (journal articles) and by the occurrence in the time interval between 2007 and 2017. The refinement by articles was done to improve the documents quality search and the time interval filter was performed to give an emphasis to the most recent publications and trends.

C. Metrics

The metrics used on the review are divided in two groups. The first group are the metrics used for an overview of the field of ABM and MAS. The metrics used for this purpose are:

- Total number of documents;
- Total number of authors;
- Total number of sources;
- Top 10 Web of Science categories and research areas per number of articles;
- Number of articles per year;
- Top 10 organizations per number of articles;
- Top 5 authors per number of articles;
- Top 10 countries per number of articles;
- Top 10 source types per number of articles;

The second group of metrics refer to a more detailed view of ABM and MAS in the field of operations research. Additionally to the metrics of the first group, the following metrics are computed:

- Total number of author's keywords;
- Total number of keywords plus;
- Average citations per document;
- Most productive h-indexes;
- Articles number per type of research;
- Articles number per ORMS subarea;
- Network visualizations;

The Bibliometrix package ([10]) was used for the network visualizations and metrics calculation.

III. RESULTS

The results present in this section are related to an overview of the articles in the field of ABM and MAS and a more detailed analysis of the ABM and MAS approaches in the ORMS research area.

A. Results for the ABM and MAS searches

The search of the terms ("agent-based model*" or "multi-agent system*") retrieved 41308 documents of the Web of Science Core Collection on June 28th 2018. By filtering just the articles, the results reduced to 18217 on the same date.

By applying the time filter (2007-2017), the total number of documents reduced to 13011. The total number of authors retrieved from the base was 24828 and the total number of sources (journals) was 2371.

Table I summarizes the first three global metrics of the study:

TABLE I: TOTAL NUMBER OF DOCUMENTS, AUTHORS AND SOURCES – ABM AND MAS

Metric Description	*Metric Value*
Total number of documents	13011
Total number of authors	24828
Total number of sources	2371

The top 10 Web of Science categories in number of articles is shown in Table II:

TABLE II: WEB OF SCIENCE CATEGORIES IN NUMBER OF ARTICLES - ABM AND MBA

Web of Science Categories	*Records*	*% of Total*
Automation Control Systems	2349	18%
Engineering Electrical Electronic	2127	16%
Computer Science Artificial Intelligence	1791	14%
Computer Science Interdisciplinary Applications	1095	8%
Operations Research Management Science	1042	8%
Computer Science Information Systems	798	6%
Economics	674	5%
Computer Science Theory Methods	666	5%
Mathematics Interdisciplinary Applications	582	4%
Multidisciplinary Sciences	581	4%

The top 10 research areas in number of articles is shown in Table III:

TABLE III: RESEARCH AREAS IN NUMBER OF ARTICLES - ABM AND MBA

Research Areas	*Records*	*% of Total*
Computer Science	4077	31%
Engineering	3608	28%
Automation Control Systems	2349	18%
Mathematics	1109	9%
Operations Research Management Science	1042	8%
Business Economics	1022	8%
Environmental Sciences Ecology	960	7%
Science Technology Other Topics	765	6%
Physics	663	5%
Social Sciences Other Topics	462	4%

It can be seen from Table II that the areas of Automatic Control, Electrical Engineering and Computer Science are the ones with the greatest number of articles, with the Operations Research area in fifth. The same trend is shown in Table III, where the Operations Research area remains in fifth with 1042 articles. The sum of the percentages in Table III is greater than 100% because more than one research area can be associated with a document.

The next metric is related to the number of articles per year from 2007 to 2017. Fig. 1 shows the value of this metric, which increases continuously since 2007. The first paper published with this subject was in 1978 and until the year 1990 just 4 articles were written related to ABM and MAS, what is an evidence of the novelty of the field.

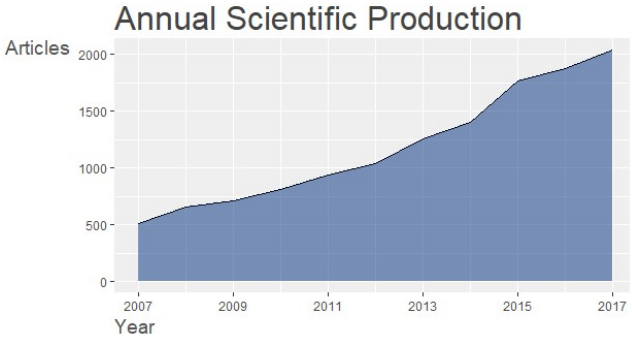

Fig. 1: Annual number of articles - ABM and MAS

Table IV shows the top 10 organizations (category "organizations-enhanced" from Web of Science). There are institutions from China (6), United States (2), France (1) and England (1). A total number of 5397 organizations have at least one publication in the field.

TABLE IV: ORGANIZATIONS PER NUMBER OF ARTICLES - ABM AND MBA

Organizations-Enhanced	*Records*	*% of Total*
University of California System	308	2.4%
Centre National de la Recherche Scientifique CNRS	283	2.2%
Chinese Academy of Sciences	235	1.8%
Peking University	186	1.4%
Huazhong University of Science Technology	177	1.4%
Southeast University China	163	1.3%
Beihang University	152	1.2%
University of London	147	1.1%
University of Michigan	146	1.1%
City University of Hong Kong	143	1.1%

Table V shows the top 10 countries ordered by the number of publications. Despite the fact that most of the top 10 organizations are from China, the overall number of articles related to ABM and MAS are from United States. A total number of 121 countries have at least one publication related to the field.

TABLE V: COUNTRIES PER NUMBER OF ARTICLES - ABM AND MBA

Countries/Regions	*Records*	*% of Total*
USA	3282	25%
Peoples R China	2991	23%
England	1054	8%
Germany	832	6%
France	720	6%
Spain	662	5%
Italy	656	5%
Canada	593	5%
Australia	582	4%
Netherlands	555	4%

The top 5 authors per number of published documents are shown in Table VI. As mentioned in Table I there are 24828 authors with at least one article.

TABLE VI: AUTHORS BY NUMBER OF ARTICLES – ABM AND MAS

Authors	*Records*	*% Total*
Wang L.	97	0.75%
Chen G.R.	47	0.36%
Huang J.	46	0.35%
Wang J.	46	0.35%
Duan Z.S.	45	0.35%

Finally, Table VII shows the top 10 source types per number of articles related to the field. Despite the fact that automation, computer science and engineering dominate the number of articles (Table II and Table III), a publication related to social sciences (JASS – Journal of Artificial Societies and Social Simulation) is the one with the greatest number of documents.

TABLE VII: SOURCE TITLES PER NUMBER OF ARTICLES – ABM AND MAS

Source Titles	*Records*	*% of Total*
JASS the Journal of Artificial Societies and Social Simulation	328	2.5%
Automatica	323	2.5%
IEEE Transactions on Automatic Control	262	2.0%
PLOS ONE	236	1.8%
IET Control Theory and Applications	227	1.7%
Expert Systems with Applications	218	1.7%
Physica A: Statistical Mechanics and its Applications	199	1.5%
Neurocomputing	191	1.5%
International Journal of Systems Science	147	1.1%
International Journal of Control	132	1.0%

B. Results for the ABM and MAS searches in the ORMS research area

The search of the terms ("agent-based model*" or "multi-agent system*") filtered by articles, by the specified time period (2007-2017) and by the research area of ORMS retrieved a total number of 1042 documents of the Web of Science Core Collection

Table VIII summarizes the first three global metrics of ABM and MAS in the ORMS field:

TABLE VIII: TOTAL NUMBER OF DOCUMENTS, AUTHORS AND SOURCES – ABM IN ORMS

Metric Description	*Metric Value*
Total number of documents	1042
Total number of authors	2356
Total number of sources	61

The top 10 Web of Science categories per number of articles is shown in Table IX:

TABLE IX: WEB OF SCIENCE CATEGORIES PER NUMBER OF ARTICLES - ABM IN ORMS

Web of Science Categories	*Records*	*% of Total*
Operations Research & Management Science	1042	100%
Automation & Control Systems	313	30%
Computer Science Artificial Intelligence	269	26%
Engineering Electrical & Electronic	254	24%
Engineering Manufacturing	168	16%
Engineering Industrial	162	16%
Computer Science Theory & Methods	147	14%
Computer Science Interdisciplinary Applications	146	14%
Computer Science Information Systems	68	7%
Management	66	6%

The top 10 research areas categories per number of articles is shown in Table X:

TABLE X: RESEARCH AREAS PER NUMBER OF ARTICLES - ABM IN ORMS

Research Areas	*Records*	*% of Total*
Operations Research & Management Science	1042	100%
Computer Science	572	55%
Engineering	544	52%
Automation & Control Systems	313	30%
Business & Economics	87	8%
Environmental Sciences & Ecology	59	6%
Geography	59	6%
Transportation	29	3%
Mathematics	22	2%
Telecommunications	17	2%

It can be seen from Table IX that the areas of Automatic Control, Electrical Engineering and Computer Science are the ones with the greatest number of articles in the ORMS field, a similar pattern than in the whole ABM and MAS field. The same trend is shown in Table X.

The next metric is related to the number of articles per year from 2007 to 2017. Fig. 2 shows this metric, which increases continuously since 2007, with the exception of the year 2012. The first paper published with the subject ABM and MAS in the area of ORMS was in 1996 and until the year 2000 just 9 articles were written, what is an evidence of the novelty of the ABM approach in the ORMS field.

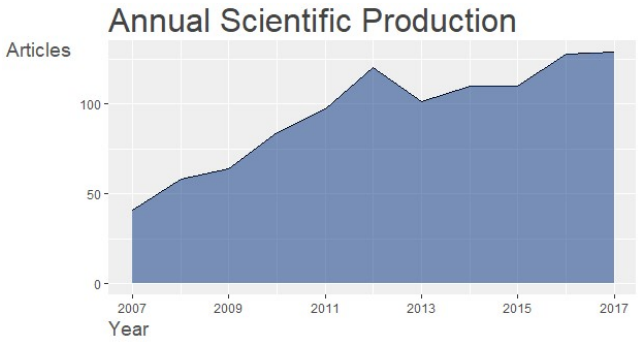

Fig. 2: Annual number of articles - ABM and MAS in ORMS

Table XI shows the top 10 organizations, where there is a prevalence of chinese institutions (9) and one from Spain. A total number of 902 organizations have at least one publication in the field.

TABLE XI: ORGANIZATIONS PER NUMBER OF ARTICLES - ABM IN ORMS

Organizations-Enhanced	*Records*	*% of Total*
Peking University	35	3%
Beihang University	30	3%
Huazhong University of Science Technology	22	2%
University of Hong Kong	21	2%
Shanghai Jiao Tong University	19	2%
Southeast University China	19	2%
Hong Kong Polytech University	18	2%
City University of Hong Kong	17	2%
Northeastern University China	16	2%
University of Salamanca	16	2%

The top 5 authors per number of published documents are shown in Table XII. As mentioned in Table VIII there are 2356 authors with at least one article.

TABLE XII: AUTHORS BY NUMBER OF ARTICLES - ABM AND MAS IN ORMS

Authors	*Records*	*% Total*
Wang L.	19	2%
Jia Y.M.	14	1%
Corchado J.M.	12	1%
Wong T.N.	10	1%

Table XIII shows the top 10 countries ordered by the number of publications. China is the country with the greatest number of articles on the field of ABM and MAS in ORMS. A total number of 54 countries have at least one publication related to the field. The majority of the publications are from Single Countries (SCP) rather than Multiple Countries (MCP).

TABLE XIII: COUNTRIES PER NUMBER OF ARTICLES - ABM IN ORMS

Countries/Regions	*Records*	*% of Total*	*SCP*	*MCP*
China	336	32%	272	64
Usa	126	12%	97	29
Spain	68	7%	48	20
England	53	5%	34	19
Canada	45	4%	31	14
Taiwan	40	4%	38	2
Italy	38	4%	28	10
Netherlands	35	3%	26	9
France	28	3%	16	12
Australia	24	2%	16	8

Fig. 3 shows graphically the countries collaboration, where China and United States are the countries with the greatest number of documents.

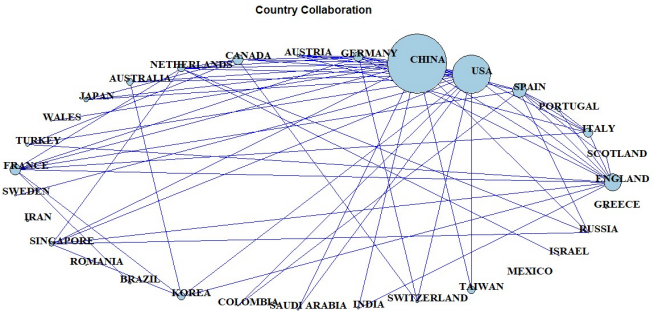

Fig. 3: Countries collaboration - ABM and MAS in ORMS

Table XIV shows the top 10 source types per number of articles related to the field. The journal "Expert Systems with Applications" and the "International Journal of Systems Science" are the ones with the greater number of publications. There is a total number of 61 different publications.

TABLE XIV: SOURCE TITLES PER NUMBER OF ARTICLES – ABM IN ORMS

Source Titles	*Records*	*% of Total*
Expert Systems with Applications	218	21%
International Journal of Systems Science	147	14%
Systems & Control Letters	126	12%
International Journal of Production Research	75	7%
Computers Environment and Urban Systems	59	6%
European Journal of Operational Research	42	4%
Decision Support Systems	39	4%
Journal of Simulation	38	4%
International Journal of Production Economics	30	3%
International Journal of Computer Integrated Manufacturing	26	2%

Total author keywords and keywords-plus, a keyword index available in Web of Science, are shown in Table XV:

TABLE XV: MOST FREQUENT KEYWORDS – ABM IN ORMS

Author Keywords	*Number of Articles*	*Keywords-Plus*	*Number of Articles*
Multi-Agent Systems	271	Networks	200
Multi-Agent System	147	Agents	138
Consensus	64	Model	127
Simulation	61	Systems	119
Agent-Based Simulation	57	Design	100
Agent-Based Modeling	42	Coordination	94
Agent-Based Model	34	Management	82
Distributed Control	30	Framework	81
Supply Chain Management	30	Algorithms	73
Agent-Based Modelling	29	Dynamics	70

The occurrence of author's keywords related to "Agent-Based Model" and "Multi-Agent System" (5 lines on Table XV) shows the focus on the methods and that ABM and MAS is close related to simulation (2 lines on Table XV). The applications is evidenced in 1 line of Table XV (Supply Chain) and the distributed nature of MAS is shown in 2 lines of Table XV (Distributed Control and Consensus).

The keyword-plus occurrences may also be graphically analyzed in Fig. 4. It is possible to see that the terms "network", "dynamics", "coordination", "algorithm" and "dynamics" with other keywords such as "delays", "synchronization", "stability" and "multiagent system" tend to appear together, evidencing subjects more related to the implementation of MAS, where aspects such as distributed computing and exchange of messages are relevant to the proper functioning of the solution. The terms "model", "system", "design", "framework", "management" also tend to occur together and are linked to other keywords such as "behavior" and "simulation", evidencing publications with more focus on the modeling and simulation and less on the system implementation.

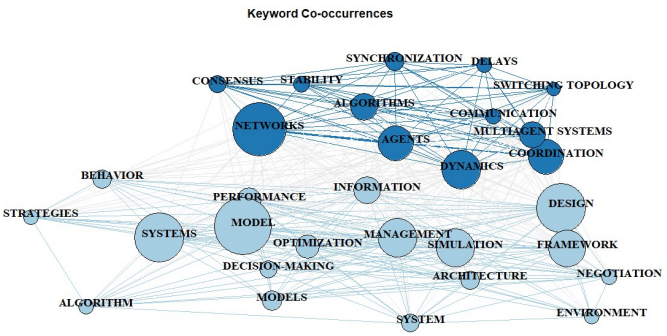

Fig. 4: Keyword-plus co-occurrences - ABM in ORMS

Fig. 5 and Fig. 6 show the average articles citations per year and the total citations per year, with a peak value for both cases in 2010.

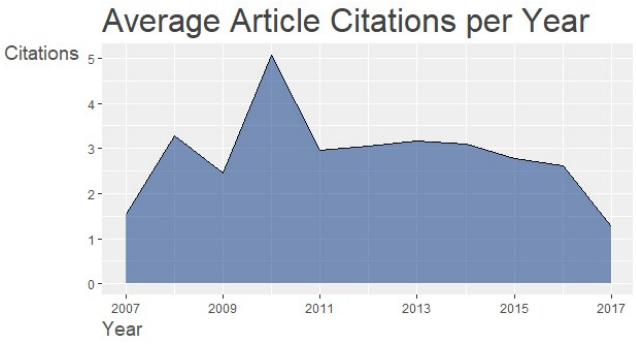

Fig. 5: Average Article Citations per Year - ABM in ORMS

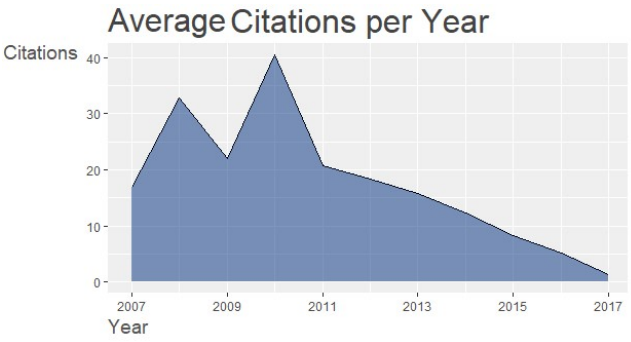

Fig. 6: Average Citations per year - ABM in ORMS

Table XVI shows the most cited references, where 3 articles are from the year 2010.

TABLE XVI: MOST CITED PAPERS AND AVERAGE CITATIONS PER YEAR - ABM IN ORMS

Paper	*Total Citations*	*Average Citations per year*
Ni W;Cheng D.Z,(2010),Syst. Control Lett.	576	72.0
Macal C.M;North M.J.,(2010),J. Simul.	443	55.4
Lin P;Ha Y;Li L,(2008),Syst. Control Lett.	354	35.4
Song QA;Cao JD;Yu WW,(2010),Syst. Control Lett.	269	33.6
Rahmandad H;Sterman J,(2008),Manage. Sci.	210	21

Table XVII shows the h-index and the total citations of the authors with the greatest number of publications.

TABLE XVII: H INDEX AND TOTAL CITATIONS OF THE AUTHORS WITH THE GREATEST NUMBER OF ARTICLES - ABM IN ORMS

Author	*h index*	*Total citations*
Wang L.	12	850
Jia Y.M.	9	430
Corchado J.M.	8	266
Wong T.N.	7	188
Bajo J.	7	248

The abstracts of the 1042 articles were analyzed and classified in terms of the OR types of research proposed by [11]. The results indicate that 64 articles are Axiomatic Descriptive, 756 are Axiomatic Normative, 90 are Empiric Descriptive and 130 are Empiric Normative. Two article abstracts were not available on the file downloaded from the Web of Science database. This indicates that most of the ABM research in ORMS is related to new theoretical methods that were not implemented or validated in real-life operational processes. The Axiomatic Descriptive and Empirical Descriptive documents are closed related to Behavioral Operations Research, since the goal is in many cases to explain processes and actor's behaviors.

The papers were also classified as proposed in the bibliometric review of [12]. The results are shown in Table XVIII:

TABLE XVIII - NUMBER OF ARTICLES PER ORMS SUBAREA

ORMS Subarea	*Number of Articles*
General Math	293
Operations and Production Mgmt.	277
Information Systems and Technology	122
Decision Making and Analysis	69
Transportation Research	67
Mathematical Programming	44
Strategy and Organizations	42
Scheduling	35
Systems Theory and Thinking	30
Entrepreneurship, Innovation and Knowledge	25
Finance	16
Graph Theory	9
Business Analytics	7
Queing Theory	2
Not Available	2
Data Envelopment Analysis	1
Other Topics	1

The great majority of articles of the subarea "General Math" are related to multi-agent systems consensus and control methods. The "Operations and Production Management" subarea encompasses a number of applications, with more articles related to supply chain, health care and emergencies situations. The "Information Systems and Technology" subarea emphasis is on platforms and information systems to support optimized operation. In the "Decision Making and Analysis" subarea are documents related to decision-making behavior and game theory.

There were few articles related to the use of ABM with Problem Structuring Methods and "Soft-PO" (3 documents), what indicates a gap in the literature of a systematic approach to combine these two disciplines.

IV. FINAL REMARKS

ABM has been utilized in a wide range of applications in a more generic sense and also inside the area of Operations Research, ranging from optimization, complex systems simulation, behavior prediction and distributed computing. The number of publications increased over the period from 2007 to 2017 and is spread across many countries, but concentrated specially in the United States and China. Due to the increasing number of articles it is a field that still has potential for research.

The great number of articles in ORMS are concentrated in the consensus and control problem, applications on operation and production management (such as supply chain) and on information systems. The greatest number of researches are of the type axiomatic normative. Despite the fact that ABM is closed linked to simulations and to a broad range of applications, not much is mentioned in the articles about the theoretical bases of how this approach can be linked to "soft" Operations Research.

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