Tendencies in Multi-Agent Systems: A Systematic Literature Review

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Abstract

The application of Artificial Intelligence mechanisms allows the development of systems capable to solve very complex engineering problems. Multi-agent systems (MAS) are one paradigm that allows an alternative way to design distributed control systems. While research in this area grew exponentially before 2009, there is a need to understand the status quo of the field from 2009 to June 2017. An extension of the results of a SLR related to Multi-Agent Systems, its applications and research gaps, following Kitchenham and Wholin guidelines are presented in this paper. From the analysis of 279 papers (out of 3522 candidates), our findings suggest that: a) there were 20 gaps related to agent-oriented methodologies; coordination, cooperation and negotiation; modelling, developing, testing and debugging; b) 24 gaps related to specific domains (recycling, dynamic evacuation, hazard management, health-care, industry, logistics and manufacturing, machine learning, ambient assisted living); and 14 gaps related to specific areas within MAS (A-Teams, dynamic MAS and mobile agents, ABMS, evolutionary MAS, and self-organizing MAS). These gaps specify lines of research where the MAS community must work to achieve the unification of the agent-oriented paradigm; as well as strengthen ties with the industry.

Keywords: Systematic Literature Review, Multi-Agent Systems, MAS Research Gaps, AOSE components.

1 Introduction

Over two decades ago, agents and Multi-Agent Systems (MAS) became a novel way of conducting the analysis, design, model and implementation of complex software systems [1]. Agents can be defined as computer systems, autonomous, and they can exhibit a flexible behaviour (to be reactive, proactive and to achieve social ability) [2]. This definition is extended by the Belief-Desire-Intention (BDI) notion [3]. A MAS contains an environment, objects and agents, relations between all the entities, a set of operations that can be performed, and the changes of the environment in time and due to these actions [4].

As a result of the growing development of relevant technologies, and the research done within the past years, agent-based systems become hailed as a new paradigm or an emerging paradigm, which is capable of many society-changing practices [5]. Other authors [3] propel the need of justifying the paradigm shift from paradigms like the object-oriented (OOP) to the agent-oriented (AOP). The engineering of MAS is a complex activity due to be implemented as a distributed system consisting of multiple agents that work together in order to solve common problems. As such, different studies have been carried out to provide a comprehensive background for specifying, designing, and implementing MAS [6-11]. Mostly, the conducted studies are rather specific than general; and so we have considered necessary to understand as well as summarize the progresses and research gaps within MAS field. The main goal was to conduct a SLR around six research questions, concerning the representative authors, the

description of the applications and their domains, AOSE components like methodologies and frameworks, and research gaps, from 2009 to June 2017 in the point of view of practitioners and researchers, in the industrial and academic context. We followed the guideline provided by Kitchenham [12], complemented with the snowballing approach [13], which begin with a set of relevant papers which will be later analyse by their citations and references in order to add papers to the original set. From the four original papers, we obtained 3522 articles through the application of the snowballing approach, and after the inclusion/exclusion criteria, only 279 articles remained.

The two main characteristics of the articles were as follows: a) dispersion based on amount of publication venues, domains; methodologies, frameworks and architectures; and b) low quantity of applications on real cases of real settings. The present study is an extension of another work by the authors [14]; and in this case, the focus was placed on the research gaps, reviewing the selected articles again and incorporating a greater number of gaps, both general and specific, into the tables; which is a huge contribution to the MAS community, achieving 20 gaps related to agent-oriented methodologies; coordination, cooperation and negotiation; modelling, developing, testing and debugging; b) 24 gaps related to specific domains (recycling, dynamic evacuation, hazard management, health-care, industry, logistics and manufacturing, machine learning, ambient assisted living); and 14 gaps related to specific areas within MAS (A-Teams, dynamic MAS and mobile agents, ABMS, evolutionary MAS, and self-organizing MAS). As a result, we strongly recommend to the MAS community that they increase their work together to unify the field, extending the bridge with other disciplines and the industry. And this would also lead to increase the amount of applications applied on real cases.

This article is organized as follows: Section 2 provides a background with previous SRLs, while Section 3 describes the systematic literature review method. Section 4 describes the results and findings. Section 5 explains the threats to validity, while Section 6 provides a brief discussion, and finally, Section 7 presents the conclusions and future work.

2 Related Work

Considering that agents are able to shape the society in which they interact, through argumentation techniques is possible to model those interactions. Carrera and Iglesias studied argumentation techniques from 1998 to 2014, and, they have concluded that *"(...) the argumentation technology is actually in a phase of internal exploration (...)"* [15]. Later on, two of the most differential aspects of agents are their autonomy, and that they are embedded in a highly dynamic environment. Some researchers introduced the Adjustable Autonomy, which allows a system not only to operate in different autonomic conditions, but also to transfer control between the system's operators. Mostafa and others described that there is no specific model or algorithm that yields viable adjustable autonomy [16]. Remembering that a reactive system must respond by taking actions to several changes that occurs in its environment; the Teleo-Reactive paradigm allows developing reactive systems like robotic vehicles. In this context, Morales and others pointed out that it is a highly promising subject of study, and that require interdisciplinary collaboration with Software Engineering (SE) [17].

Likewise, Agent Oriented Software Engineering (AOSE) allows to apply the principles from SE and AI to the life cycle of a software system [8]. Blanes and others identified the Requirements Engineering (RE) techniques that has been applied while developing MAS, and they found out that 79% of the papers used methods or techniques from existing paradigms; and that 69% of these methods and techniques were built on the goal-oriented paradigm [17]. Similarly, Juziuk and others found out only 206 Design Patterns (DP) since 1998, from that they have concluded that there is no standard template to help with the process of DP documentation for MAS, the associations between patterns are poorly described and the classification of patterns are tied to specific DP lists [19].

There have been domain-specific studies within MAS field, such as health-care and marketing. In the first case, Isern and Moreno showed the viability of applying and implementing agents within the health-care domain, and from which it can be concluded that agents applied in health-care is a growing field. In the second case, Negahban and Yilmaz provided an analysis in marketing, where they pointed out that several Agent-Based Modelling and Simulation (ABMS) application within conventional markets and new product diffusion have been described in a high number of studies; demonstrating the capability of ABMS to capture and model emergent phenomenon [20].

As can be seen in the previous descriptions, systematic studies address research questions on a specific topic such as argumentation techniques or design patterns; from which it is possible to say that the decreasing trend of publications does not affect specific domains or modelling and simulations. However, we have not found studies that share the same scope as the present work, which approaches the identification from 2009 to June 2017 of the progresses, AOSE components, MAS applications, domains, representative authors, and gaps. The following sections will describe the review method and the answers to the research questions.

3 Review Method

The present SLR followed the guidelines provided by Kitchenham [12], and complemented through the search approach known as snowballing defined by Wohlin [13].

3.1 Research Questions

According to the goal presented, we formulate the following set of Research Questions (RQs), where RQ1 concerns to the general objective, RQ2 and RQ3 allow identifying and characterizing authors and communities, while RQ4 to RQ6 address topics related to applications, and finally RQ7 allows the identification of SMA gaps. The list of RQs is the following: *Research Question 1 (RQ1):* What are the articles that represent an up-to-date SMA state-of-art?; *RQ2:* Who are the most representative authors?; *RQ3:* What are the main publication venues?; *RQ4:* What are the most applied methodologies, frameworks, and programming languages?; *RQ5:* What are the most selected application domains?; and *RQ6:* What are the research gaps?

To address RQ1, we performed the review method described earlier, in order to find those relevant papers that will lead us to obtain a proper collection of the published projects or researches from 2009 to June 2017 within the MAS field. Also, 2009 was considered as the starting point due to the publishing of a book [2] (with a growing number of citations - 11047 to January 2, 2019, and a verifiable background of the authors – see [1], [21]) which provided an introduction and compilation of all the main theoretical and practical topics from intelligent agents and MAS.

3.2 Inclusion and Exclusion Criteria

Articles published between 2009 and June 2017 were **included** if they fulfilled the following topics: (a) the title and/or the keywords (if exists) should contain "multi-agent systems", "multiagent systems", "intelligent agents", "agents", "MAS" or similar phrases, (b) studies which were directed related to MAS techniques, approaches, challenges, implementations, gaps or limitations; (c) studies that were directed related to AOSE components; (d) studies related to MAS implementations and case studies applied to different domains; (e) studies whose type were surveys, systematic reviews, review, case studies, formalization, applications. Papers on the following topics were **excluded**: (a) studies on a non-English language; (b) duplicate or updated studies (we selected the most recent one); (c) journals with low impact factors; (d) books; (e) extended abstracts; (f) technical reports; (g) doctoral dissertations; and (h) thesis.

3.3 Search Strategy

In order to obtain a proper set of relevant papers for this review, we conducted a manual search, an automated search and the snowballing approach.

3.3.1 Manual Search

One of the authors performed a scan of publication venues and journals, to attain a panorama of communities and publishers in subjects related to multi-agent systems. From this search, systematic reviews and books were obtained that allowed us to put together the RQs, as well as the inclusion and exclusion criteria. Also, the Cohen's Kappa statistic [22] was used to perform an evaluation of the reliability of the inclusion and exclusion decisions between the raters (the authors), which gave a value of 0.75, showing the level of agreement.

3.3.2 Automated Search

After the manual search, we queried Google Scholar based on [10], using {*systematic review; multi agent systems*}, and we judged the relevance of the results to the RQs based on title, and publication year. In due consideration that the content of the databases and index vary over time, the actual search was conducted on June 2017. As a result of this step, one of the authors identified 9 candidates for inclusion (reviewed by the other one). Even though Giustini and Boulos [23] pointed out that "*Google Scholar does not meet the required search standards for conducting a SLR*", our main target was the next step (snowballing) in order to discover patterns and update the knowledge on the field. The 9 articles were analysed regarding the abstract, references and citations; from which 4 articles were selected to form the start set, denoted as S1 to S4.

3.3.3 Snowballing

Following [13], we put together the initial point of analysis: S1 had 74 references and 4 citations; S2 32, and 3; S3 161, and 3178; and, finally S4 34, and 36. As is it possible to observe, the search produced a large number of potentially relevant papers (3522 to be exact). These papers were assessed for inclusion or exclusion against the

specified criteria previously defined. Only one iteration has been performed. Articles S1, S2 and S4 were tested by implementing the iterations with the backward and forward snowballing procedures. S3 was only studied by forward snowballing due to its publication year. From S1, S2, and S4; 140 candidates were evaluated, and 16 new papers were included, denoted S5 to S21. Later, forward snowballing was applied to the full start set, leaving 3221 citations to evaluate, from which 259 were included, denoted as S22 to S279.

3.3.4 Data Extraction and Synthesis Methodology

We created a form to consolidate the data extraction, in which the following items were completed for each article by the two reviewers: (a) author (full name, affiliation and institutions/universities, country, amount of papers), (b) amount of citations, (c) publication year, (d) source (journal, conference, congress, workshop, symposium), (e) publisher, (f) developed applications: domain, availability, license, framework, programming language, architecture, platform, methodologies, (g) new programming language architecture, platform or methodology, (h) type of study, (i) research gaps, and (j) scope. Also, another spreadsheet was used to perform the mathematical analysis over the values and amounts. To obtain the 'most representative' authors, the articles were filtered, on the one hand for the amount of citations for each one of them, and on the other hand, for the amount of papers within the full set of papers (279). From that and in first place, we filtered the top 20 ordered from higher to lower number of citations from which we obtained 64 different authors. Secondly, by choosing each of the authors of the top 20, we correlate each of the articles in which he/she appeared as author (1 to 7 papers) with the number of citations for each of those articles; in order to obtain the sum of all the citations for the total articles of each author.

4 Results and Findings

4.1 Overview of Papers

Our findings suggest that between 2009 and 2017 there has been a few stellar years, as illustrated in Fig. 1. The year with most publications is 2009 with 65 articles, followed by the other years in ascending order, with a minor change in the list where 2015 obtain three more papers than 2014. Unfortunately, the general trend line for agent-based oriented papers is decreasing, also exposed by Balke and others [24] who examined the main track proceedings of AAMAS from 2006 to 2011 (the amount of application papers decreased from 10% to 6%). Nevertheless, finding 4.1 shed light onto the trend (see for example [10] in healthcare).
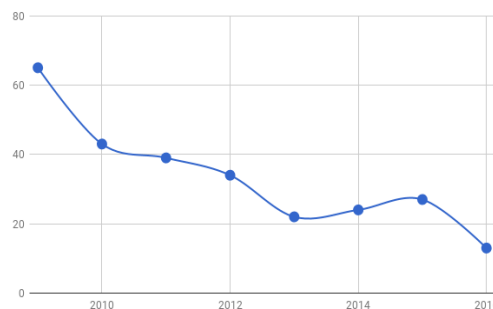

Figure 1: Trend line of analyzed articles per year

Finding 4.1. There is a general decreasing trend of publications, but an increasing trend within specific fields.

Regarding the papers, 69.8% of the selected articles were applications while the remaining 30.2% were researchers studying the MAS paradigm and performing SLRs, surveys, theoretical formalizations, among others. Within the applications, only 22.56% of the articles portrayed a real case study, and the other 77.44% were controlled case studies through simulations, evaluations, comparisons, test bed, and empirical evaluations through practical metrics; leading to obtain experimental results.

Finding 4.2. Approximately 82% of the studies were conducted within the academia, 16% in cooperation with industries and businesses, 6% without the academia.

Considering the full amount of articles, 82% of authors belonged to departments, faculties, institutes, and/or laboratories of approximately 250 universities globally distributed. While the remaining 16% (6% developed and owned without the academia) is represented by industry leaders such as Ansaldo Segnalamento Ferroviario; companies such as Portugal Telecom Inovação e Sistemas; councils such as the National Council for Scientific and Technical Research (CONICET); research centres such as IBM T.J. Watson; and state services such as Meteorological Service of Cyprus; just to name a few examples.

These values showed an update on the values presented in [9], and based on an analysis of 152 applications. From 28% of applications within academia and a 41% built in industry-academic cooperation, our findings (based on 194 applications) suggest an increase of 54% on the first players, and a decrease of 25% for the second players. Nevertheless, only 10 applications provided a link to the code of the implementation, or at least to some libraries to download. Then, 70% of the application papers described the amount of agents, which varied from two to fourteen agents.

4.2 RQ3: What are the main publication venues?

Regarding to the 102 journals obtained, approximately 71% of the articles correspond to 48 different journals with one article each, which it is related to the affirmation that broader communities of researchers in MAS are publishing not in a few journals (and conferences, workshops), but in several and every time within more and more specific domains. The Top 3 of **Journals** are *Expert Systems with Applications*, *Information Sciences*, and *Autonomous Agents and Multi-Agent Systems*; where the Top 2 of **Conferences** are *International Conference on Autonomous Agents and Multiagent Systems*, and *KES Conference on Agent and Multi-Agent Systems – Technologies and Applications*. Likewise, from 95 conferences, approximately 87% of them have only one article, again evidencing the dispersion. Also, the number of congresses (4) and symposiums (11) is low while the journals (102) and conferences (95) take the largest number of representatives. Each of them provide a means of discussion or practical work on a particular topic, allowing speakers and assistants to share their knowledge, experience, suggestions; due to the fact that as scientific and technological advances, it presupposes a higher level of specificity of topics and domains to achieve a feasible solution. In addition, interdisciplinary work is fundamental to that goal, because it also opens doors to unknown but rich territories.

Finding 4.3. The articles were mostly published in journals (44.7%) and conferences (42.7%).

4.3 RQ4: What are the most applied methodologies, frameworks and programming languages?

Several papers enumerated distinct and well-known methodologies such as Gaia, MaSE, O-MaSE, INGENIAS, AGR, Tropos, Prometheus, among others; but only 20% of the analysed studies explained the chosen methodology that was part of the implementation. The most used methodologies were Gaia and Prometheus. From 2009 to June 2017, new domain-specific methodologies have been formalized like mechatronic and environmental systems, traffic lights, supply chain, among others. We have found that some researchers have extended a well-known methodology based on some necessities or on problems identification within the formal definitions. On the one hand, Prometheus was extended to improve the requirements understandability, and maintainability through the automatic generation of activity diagrams [25]. On the other hand, Gaia is extended in [26] to make it more practically applicable as model-driven engineering, and extended in [27] with the security model.

Finding 4.4. There are new domain-specific methodologies, and Prometheus and Gaia have been extended.

The existence of several methodologies have stimulated the creation of multi-agent programming languages (PLs) and frameworks [28]. 44 of 195 applications provided data about the PLs used in the development. Java (not agent-oriented) has been the most popular PL used in 18 applications. C, C++, C #, and Jason followed it. Within the agent-oriented PLs, there are individualities such as the Jazzyk language in gaming, Jadex used in bankruptcy contagion effects, and tuProlog in railway signalling.

Finding 4.5. Java was by far the most used PL in 18 applications (of 195).

With respect to frameworks, 64 of 195 applications provided information about the framework used. In our case, JADE was the most used framework out of 36 applications. Even though the sample is small (56% out of 64 applications), our findings are consistent with what some authors have put forward about the most used frameworks [9] meaning that JADE, and JACK, remain as the most used agent development frameworks.

Finding 4.6. A) JADE was by far the most used framework in 36 applications (of 195), mainly in traffic, transport, logistics, and manufacturing; B) There are new domain-specific frameworks, as well as new frameworks for MAS themes and topics; C) Based on A), a detailed analysis of JADE is required.

Following C) within Finding 4.6, it is possible to say that even though some companies have been interested in the development of MAS, point A) is indeed an academic point of view; due to the fact that the authors have performed an analysis of existing documentation, and they did code tests and reviews. From those, some issues have been found: JADE has a deprecated Android version, it also shows deficiencies within the SOAP protocol. Likewise, there is a lack of future maintainability of any application developed with JADE, and even though it is open source it does not have a public repository on Git, and finally, it is a verbose framework [29].

4.4 RQ5: What are the most selected application domains?

The distribution of 195 applications were given by 16 different domains, which are the following: information science (D1), transport / traffic / ports (D2), health-care / medicine / biology (D3), networks (D4), logistics / manufacturing (D5), mechatronics (D6), business (D7), economy / finance (D8), earth related (D9), energy (D10), education (D11), security (D12), food and agriculture (D13), games / entertainment (D14), electronics (D15), and finally, chemistry (D16). From Figure 2, it is feasible to calculate that six domains cover 72.9% of all applications while the remaining 27.1% is covered by 10 domains.
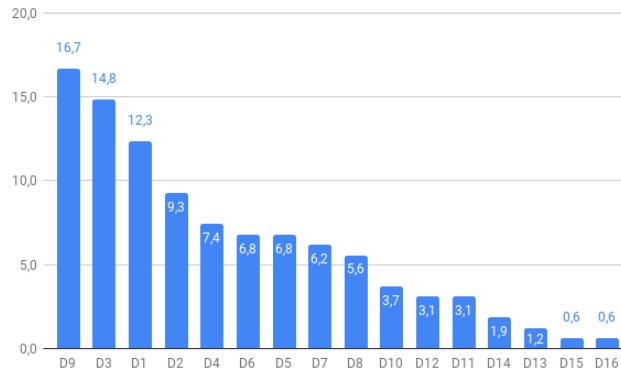

Figure 2: Column chart describing the values per domain as total, without separating ABMS from pure MAS implementations.

Finding 4.7. A) The top three domains on modelling and simulation were transport/traffic/ports (D2), health-care/medicine/biology (D3), and logistics/manufacturing (D5); B) The top four domains for multi-agents implementations were health-care/medicine/biology (D3), information science (D1), logistics/manufacturing (D5), and business (D7).

4.5 RQ6: What are the research gaps?

By reading each of the included articles, it was possible to extract the gaps mentioned and found by the authors. As such, we were able to schematize the research gaps into two groups: the ones related to the paradigm itself paradigm itself (see Table 1), and those related to specific application domains or disciplines (see Table 2). Consequently, in Table 1 is possible to find gaps related to agent-oriented methodologies; coordination, cooperation and negotiation; modelling, developing, testing and debugging, and metrics; while Table 2 describes those related to specific domains (recycling, dynamic evacuation of pedestrians, hazard management, health-care, industry, logistics and manufacturing, machine learning, and Ambient Assisted living (AAL)) or specific areas within MAS (A-Teams, dynamic MAS and mobile agents, ABMS, evolutionary MAS, and self-organizing MAS).

Table 1: General Research Gaps

Topics	Description of General Gaps
Agent-Oriented Methodologies	- Absence of systematic methodology (Sturm, Dori, & Shehory, 2010). - None of the modeling languages is widely accepted and used (Sturm, Dori, & Shehory, 2010). - "It seems that existing agent-oriented methodologies focus on the development of new systems and not on other stages and aspects within the system lifecycle. Even with reference to development process, not all phases are well supported" (Sturm & Shehory, 2014). - "Another void is the lack of support for a paradigm shift to agent orientation. We believe that the latter is a grand challenge for agent-oriented methodologies. That is, it is necessary—yet challenging—to justify the paradigm shift from existing paradigms such as object-oriented, service-oriented, and business-process-oriented to the agent-oriented paradigm" (Sturm & Shehory, 2014). - "While a number of modeling languages for constructing multi-agent systems (MASs) have been suggested, none of them is widely accepted and used. A prominent reason for this is the gap between agent-oriented modeling languages and the agent-based system modeling needs, including accessibility, flexibility, and expressiveness" (Sturm, Dori, & Shehory, 2010). - "Put more effort into integrating agent-based methodologies and programming languages" (Dastani et al 2009).
Coordination, Cooperation and Negotiation	- "Advocate time to understand when agents need to communicate" (Lang & Fink, 2012). - "An open question is the analysis of coordination problems with larger number of agents" (Lang & Fink, 2012). - "Some important problems in multi-agent system research are: how to enable the agents in the system to communicate and interact with each other? what kind of communication language and protocol do they use? how to coordinate the multiple agents in the system to achieve a common system goal through their communication and collaboration?" (Wu & Sun, 2010)
Testing,	- "Study how to employ the debugging frameworks that are available for the embedded languages (such as Prolog or a

Topics	Description of General Gaps
Debugging	Web Ontology Language (OWL))". (Dastani et al 2009). - "A debugger for agent programming in general is needed" (Dastani et al 2009). - "Recent developments in multi-agent programming languages have proposed specific programming constructs enabling the implementation of social concepts such as norms, roles, obligations, and sanctions. Debugging such multi-agent programs requires therefore specific debugging constructs to specify properties related to the social aspects and facilitate finding and resolving defects involved in such programs" (Dastani et al 2015) - "A debugger for multi-agent programs that run simultaneously on different platforms is also needed" (Dastani et al 2015). - "There are more challenges in debugging cognitive agents that need to be addressed. One of these is the fact that agents are (usually) connected to an environment. Two problems need to be dealt with: (i) it can no longer be assumed that an environment is deterministic which makes it difficult to reproduce a defect, and (ii) such environments typically cannot be suspended instantly which makes it difficult to understand the context of a defect. Another problem is the fact that debugging multiple agents at once is significantly more complicated than debugging a single agent. Finally, to further analyse the effectiveness of a source-level debugger in agent programming in general, a detailed design of a source-level debugger for other agent programming languages can be of interest. It would be specifically interesting to investigate the effect of a more complicated decision cycle on the usability of a source-level debugger" (Koeman & Hindriks, 2015) - "Studies and work on testing should increase" (Leitão & Vrba, 2011). - "We believe that comprehensive automated unit testing is a critical first step in thorough testing of agent systems. However, it is limited in what it tests for" (Zhang et al, 2011) - "Further research in the area should focus on developing and testing more advanced coordination methods, which could be used in real-time applications. Tests on large groups of real robots should also be performed" (Turek, 2010)
Developing	- "It is time to start paying more attention to the kind of support that a MAS developer needs to facilitate him or her when engineering future MAS applications. It is important to identify the needs of a developer and make sure that a developer is provided with the right tools for engineering MAS. For the same reason we should focus more on issues related to ease of use, scalability and performance, and testing" (Hindriks, 2014)
Modelling	- "There is a need to bridge the gap between modeling and implementation, i.e., creating guidelines or rules for synthesis of runnable agents from the abstract modeling components" (Lian et al, 2009)
Metrics	- "The need for software metrics is now fully recognized" (Leitão & Vrba, 2011).

Table 2: Domain-Specific Research Gaps

Topics	Description of Domain-Specific Gaps
Recycling	- "Automate communication and cooperation of parties involved in the collection process" (Bezirgiannis & Skaellariou, 2011). - "Lack of modern tools for managing the collection of recyclable resources" (Bezirgiannis & Skaellariou, 2011).
Dynamic evacuation of pedestrians	- "Improve the studies on: the impact of mixtures of groups and mixtures of spatial areas, stairway and exit capacities for individuals with disabilities, the speed and mobility over different surfaces to increase the realism of the evacuation models" (Manley, et al 2016).
Hazard management	- "Future studies should pay attention to encoding learning algorithms and reconstructing the hazard-management processes in historical events (e.g. Hurricane Katrina). Constructing geographic ontologies is so challenging that no commonly shared ontology is yet available. Managing large-scale natural hazard events often involves multiple decision makers in different disciplines or cultures across regions or countries; thus building a sharable ontology is crucial for sharing information and reducing misunderstanding or miscommunication" (Yu et al, 2009).
Health-care	- "The majority of work done is domain specific like patient scheduling" (Benhajji, N., et al 2015). - "Consider the advancements in biomedical sensor nodes capable" (Shakshuki & Reid, 2015). - "Increase the amount of multi-agent applications design to prolong the independent lifestyle of seniors" (Shakshuki & Reid, 2015).
Industry	- "Within the steel industry, a steel automation system is needed to represent distribution and integration. Using multi-agent systems depicts such capabilities." (Zarandi, et al. 2009). - "It would be useful to provide demonstrators running in industry and return of investment (ROI) analysis, not only in terms of development costs but also in terms of operation and maintenance costs" (Leitão & Vrba, 2011) - "Lack of widely available industrial-strength multi-agent system toolkits" (Jennings et al, 1998) - "the main future trends for industrial agents are centered on: - Consideration of mature tools and development engineering methodologies that simplifies the engineer of agent-based systems (integrating the design, verification, simulation, and deployment phases) and also supporting technologies to run agent-based solutions, e.g., at low level control. - Consider the integration with other technologies, namely the integration with the low-level control running in state-of-the-art PLCs running IEC61131-3 control programs or using the IEC 61499 standard since the direct connection with physical devices is usually mandatory in industrial environments. Aiming to address other integration vectors, namely the IT-vertical integration, the combination with web services should be considered to address the questions related to the interoperability. - Consideration of bio-inspired techniques, and particularly self-organization and emergent behaviour, enhancing multi-agent systems to support the engineer of more robust, adaptive, reconfigurable and responsive systems. - As highlight by industrial experts, the consideration of standardization issues in the development of agent-based solutions, namely the IEC 61131-3 and ISA 95 standards, is crucial. Note that the Foundation for Intelligent Physical Agents (FIPA) is a standard for the development of multi-agent systems, but it misses many of the particularities imposed by industrial environments" (Leitão & Vrba, 2011) - "FIPA misses many of the particularities imposed by industrial environments" (Leitão & Vrba, 2011).
Logistics and	- "New architectures of manufacturing automation systems are required to implement a smart factory" (Gohner &Weyrich, 2014).

Topics	Description of Domain-Specific Gaps
manufacturing	- "Detailed parallel simulation formalisms for multi-agent systems are needed" (Tan et al, 2011). - "Within the multi-level supply chain decision making, further research should focus on conducting experiments with heavily traded products" (Hernández et al 2014). - "There is a need for efficient automation architectures in engineering, commissioning and test processes" (Hernández et al 2014). - "The amount of application studies in real industrial cases is low" (Hernández et al 2014).
Machine Learning	- "Future research should help to further integrate both fields – agent technology and machine learning. Agent based solutions could be used to develop more flexible and adaptive machine learning tools. Collective computational intelligence techniques can be used to effectively solve computationally hard optimization and decision problems inherent to many supervised learning techniques and data reduction problems. Most promising direction for future research seems integration of machine learning and agent technology with a view to obtain effective solutions to the distributed learning problems. On the other hand more compact and reliable machine learning techniques are needed to equip agents with better learning capabilities" (Jędrzejowicz, 2011)
Ambient Assisted living (AAL)	- "On the other side there are still gaps and obstacles between innovative AAL systems and different aspects of participants within the system. In the future, more user studies should be performed regarding the acceptance of AAL services and devices by the users, usability as well as the users' expectations of such assistive services. It is also essential to bring together all the stakeholders and enable the very important networking between policy makers, developers, producers, service providers, end user organizations, designers, health professionals (medical doctors, psychologists, rehabilitation nurse etc.), sociologists, home carers, older adults and other potential end user groups" (Li et al, 2015) - "More user studies should be performed regarding the acceptance of Ambient Assisted Living (AAL) services and devices by the users, usability as well as the users' expectations of such assistive services" (Li, R, et al 2015)
A-Teams (asynchronous team of agents)	- "Available platforms hide all complexity of the distributed architecture and offer sets of predefined objects available to users who can focus on the logic of the A-Team applications and effectiveness of the optimization procedures rather than on middleware issues. A-Team technology is ready to offer functional, scalable, flexible, efficient, robust and stable A-Team architectures" (Jędrzejowicz, 2009).
Dynamic MAS and mobile agents	- "The use of dynamic MASs enables taking advantage of some of the properties of agents such as reactivity, proactivity, and sociability. One of the main weaknesses of such solutions is the defense mechanisms of the MASs, as the resistance to attacks has not been considered in most previous work" (Herrero & Corchado, 2009) - "Although mobile agents can provide an IDS with some advantages (mobility, overcoming network latency, robustness, and fault tolerance), some problems have not been completely overcome yet: speed, volume of the code required to implement a mobile agent, deployment, limited methodologies and tools, security threats, and so on" (Herrero & Corchado, 2009)
ABMS	- "Future research can explore the use of adaptive techniques like genetic algorithms and cased-based reasoning as part of agent-based simulations" (García Camino et al, 2009) - "This makes agent-based simulation a favorable tool for decision makers, especially those who are active in the electric power market. Although any agent-based electric market models have been designed there is still a need for a more flexible model having not only the ability to examine strategic behavior within a certain market framework, but also to evaluate the performance of the market framework compared with other existing or even new ones" (Maenhoudt & Deconinck, 2010) - "There is a clear need for further research regarding the actual simulation models. More simulation models need to be done. This kind of research should not only include some general information about the model and its results; there is also a need to know the pitfalls during the simulation processes. This information is valuable to modelers and it would improve the quality of integrated models. As there is still a small amount of hybrid models, it is expected to see the amount of actual simulation models first to increase before the amount ES with hybrid models increases. However, the advantages of hybrid simulation models are clear and they will increase the value of the Expert System (ES). Hybrid ES should be tested against conventional ES to see whether the use of hybrid simulation model improves the accuracy of the ES" (Lättilä et al, 2010). - "Outcome of an ABM is difficult to assess" (Chen, 2012) - "the application of agent-based modelling and simulation in analysing digital markets seems to be in its early stages" (Negahban & Yilmaz, 2014) - "Taken together the findings and limitations suggest several promising areas for future research. In particular, studies examining the impact of mixtures of groups and mixtures of spatial areas such as corridors and stairways would enhance the understanding of evacuation dynamics during crisis situations. Likewise, studies examining optimum stairway and exit capacities for individuals with disabilities would be of great value considering the pivotal role these features play in an evacuation. Lastly, empirical studies of speed and mobility over different surfaces would lend further realism to this and other evacuation models" (Manley et a 2l, 2016) - "For knowledge representation, it is important to consider the following three themes: a) development of representation standards, b) methods for knowledge acquisition from heterogeneous sources, and c) time representation. Also, an immediate need is to develop a protocol or standards to allow diverse knowledge representations to be sharable and interchangeable. Likewise, it is important to develop new approaches for capturing heterogeneous sources of geographic knowledge. In addition to space–time representation, it is necessary to build temporal knowledge bases and congruous interactions among the distributed knowledge/data representations for better representation of geographic processes" (Yu & Peuquet, 2009).
Self-Organizing MAS	- "The study on application of self-organizing MAS is still in early stage" (Ye, D, et al 2017). - "Future research should focus on devising an efficient methodology or tool, applying self-organizing reinforcement learning in physical systems to improve the learning performance, and introducing self-organization into coalition formation and evolution of cooperation" (Ye, D, et al 2017).
Evolutionary MAS (EMAS) – a class of auto-adaptive MAS	- "Some approaches developed in theoretical analysis of evolutionary algorithms take into consideration only particular cases of algorithms" (Byrski et al, 2015). - "EMAS researchers should carry on with the constructions of formal modelling focused on researching different asymptotic features, building infrastructure and tools that support the implementation of various systems" (Byrski et al, 2015).

Finding 4.8. A) There is a lack of unified tools (methodologies, framework, among others) that developers can use to implement a MAS; B) The work done is mostly domain-specific; C) the MAS community should build ties with the industry; D) a detailed design of a source-level debugger for other agent programming languages can be of interest; E) There is a need to bridge the gap between modelling and implementation; F) FIPA misses many of the particularities imposed by industrial environments; G) Constructing geographic ontologies is so challenging that no commonly shared ontology is yet available.

Following finding 4.8, it is feasible to say that the MAS community should keep working on closing the gaps shown in Tables 1 and 2. Consequently, these Tables not only demonstrate that there has been advances in specific fields, but the resolution of the most critical or unresolved aspects of the domains, whose resolution would help to mature the paradigm, remain pending.

5 Threats to validity

A few articles from 2017 were not available to download while we were performing the analysis of each paper, from which some papers could be added to that period modifying a little bit the amount of papers published that year, and that is the main reason because we did not include them in Fig. 1. Likewise, it is feasible to point out that the trend shown in Fig. 1 might be influenced on the loose of interest in that particular publication (S3), but it is compensated by the validity of the rest of the articles of the start set (2014 and 2015). Consequently, in this article, the factors, which jeopardize internal validity, are as follows: a change within the followed method may produce changes in the outcomes, a broader range of years, and the inclusion of the papers that were not available when the SLR was carried out. Also, in order to provide a fearful basis onto the automated search, one of the authors performed a search on online databases to obtain the amount of articles for 2015 (based on Fig. 1) with "survey multi-agent systems" on publication title. As a result, we obtained two articles from ACM and none from Springer.

One of the articles was excluded based on the title, and the second one was a tutorial on NetLogo (excluded as well). Consequently, GS were a valid source to conduct the search. Nevertheless, one of the main limitations of this study is that maybe some good papers were excluded because they were not referenced in any of the four papers that made up the start set or that did not cite at least one of those four papers. For that, another iteration might be sufficient to fully complete the start set. Or even, including text-mining techniques to improve the search. For these reasons it is not possible to generalize the results, but it is necessary to understand that they respond to a partial sample, but not negligible.

6 Discussion

Different authors [3, 8] mentioned the need of justifying the necessity for a 'paradigm-shift' from existing paradigms to the agent-oriented paradigm; which it will require a change within the basic concepts and practices within each discipline and domain of application. In this context, a shift will be supported if and only if there is a broad adoption and acceptance of the technology itself. So, is the MAS community using solely AOSE components? Or is it using a combination of the object- and the agent-oriented paradigms? Is the latter ready to take-off individually? There is no doubt about the need for a new paradigm evidenced in the number of domains in which MAS have been applied, but does it satisfies all the needs to face highly complex applications?

Back in 1998, there were two major technical impediments to the widespread adoption of agent technology [30], where the first one concerned to the absence of a systematic and unified methodology, while the second one was related to the lack of industrial-strength MAS toolkits. Up today, there is a diversity of methodologies that many of them share a common basis, and new methodologies for specific domains have been developed. However, none of the modelling languages is widely accepted and used [31]. The actual agent-oriented methodologies are mainly focused on the development of systems, but without contemplating other phases or stages [8]. Consequently, further progress must be made so that MAS technologies can cover the entire software life cycle [32].

In addition, the life cycle models should support reusability. The reuse of code and concepts are important when developing MAS, and Schumann [33] presented an approach to effective and efficiently select mechanisms to coordinate plans among agents. The following question arises at this point: can we expect from MAS a paradigm that covers all phases of the life cycle of the systems or is it just an extension of OO, with complexity, autonomy, parallelism, feedback from the environment, and emerging behaviour; applicable in certain parts of a system or phases of the life cycle?

Several studies explained that Java and JADE are the most used programming language and framework respectively, within the agent-oriented applications [9], but both of them comes from the OOP. Even though JACK is the most used agent-oriented framework, JADE is applied in a higher amount of applications. Based on our knowledge, we recommend the programmers to perform a proper analysis before implementing JADE, due to the fact that is deprecated. Likewise, programmers who are up to new challenges (considering the learning curve) might select directly a multi-agent programming modelling environment like NetLogo. However, is it fully justified the

learning curve? From previous experience of the authors, it is feasible to say that the generated code is difficult to maintain when it evolves and is useful for simple simulations.

The second major impediment was related to the lack of widely available MAS toolkits powerful enough to be used in industrial settings [30]. There are several challenges that have a huge impact on the acceptance of industrial agents [34,35]. As such, a shift is needed within industrial environments for automation vision because it portrays a decay of the applicability, and real deployment of the agent technology [35]. Even though the industrial adoption and application of agent technology is endorsed by different initiatives by International Technical Committees and R&D projects, the contemplation of standardization matters within the development of agent-based solutions is decisive. In the MAS context, the integration and feedback from the industries and business that have already used or develop a MAS, would be extremely useful to improve the existing bonds and create new ones on industrial settings. As Muller and Fischer mentioned *(...) "the strong presence of Spain and Italy for highly mature applications is based on the strong industrial players Telefonica T+D and Telecom Italia" (...)* [9].

Nowadays, and as a part of the regular progress of the Software Engineering field, the requirement for software metrics is now fully recognized by the community [36]. Even though the reasons for defining and implementing metrics are independent of the chosen paradigm, the latter have an impact on the set of metrics to employ [37]. Also, within the advances in technologies, the application of agent-based solutions to machine learning have proven to harvest a synergetic effect within the power of achieving cooperative solutions implemented by interactions between agents. For that, *(...) "machine learning can be seen as a prime supplier of learning capabilities for agent and multi-agent systems, while agent technology has brought to machine learning several capabilities including parallel computation, scalability and interoperability" (...)* [38].

Finally, as seen in Tables 1 and 2, it is possible to say that although the paradigm tended lines of growth with respect to its origins, today there are still gaps as the absence of a systematic methodology and toolkits for the industry; which are drawback points at the moment a project leader decides whether to implement a multi-agent system or not.

7 Conclusions

In the present article, a systematic literature review was carried out around six research questions, following a well-known guideline [12], and complemented with the snowballing approach [13], in order to understand the progresses of Multi-Agent Systems, from 2009 to the present days. After applying the snowballing approach of the 3522 candidates, only 279 remained, which were estudied in the industrial, and academic context.

We have obtained 67 representative authors from 49 countries, who have obtained a range between 41 and 248 citations per each related to the amount of articles within the 279 articles analyzed, and who have published in 102 journals, 111 conferences, 11 symposiums and 4 congresses. Almost 30% of the applications achieved one of the three levels of maturity presented in [9], mostly in academia but within the cooperation with industry and public administration. These numbers make up the first topic that makes a consistent and repeating feature in the answers to all the research questions: dispersion. Likewise, we have found a high number of domains in which MAS have been applied which lead us to understand that there is not a single possible domain of application, which gives us variety and dynamism. This dispersion also means that the field is growing, is becoming more specific and bounded, but how do we manage to unify it? How do we support the learning curve of developers?

Besides, what are the causes of the decrease in the general number of publications? It corresponds to a depletion of the paradigm, to the lack of adequate tools, a low level of industrial assimilation, to the non-integration of the different branches that emerged from the growth and specification of the field? Or is growing domain by domain? MAS is an area that, although it requires work to close and unify the threads, makes it possible to tackle complex systems in a changing and increasingly complex world.

The research gaps show that there is a need to fully close existing and old topics within the MAS field: ties with the industry (as well as a widely available MAS toolkit) and a systematic methodology of developing. As such, if the community wants to fully integrate multi-agent systems within industrial settings, they should develop industrial toolkits that adapt to the particularities in force in the industry, and increase not only the amount of applications but the applicability in real life. Likewise, the MAS community should learn from the history of the object-oriented paradigm. As such, if there is no industry acceptation then there is no growth and sustainable maturity to be a true paradigm.

Even though the improvement in computing power *(...) "has increased the scope of MAS employability in real-world applications" (...)* [39], as Dawson-Díaz and Vega-Zepeda [40] stand, and following Tables 1 and 2, we can conclude that there is no standardized process for creating Multi-Agent Systems, and the fact that many methodologies do not cover the whole lifecycle, might lead to a non-allowance of using this technology within the industry. Is the author's beliefs that a standardization of terminology and methodology [8] would lead to the maturity of the paradigm, as years ago UML and the Unified Process (UP) had an impact on the object-oriented

paradigm; recalling that at the time they participated in the unification of language and methodology people from academia and industry.

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Appendix (if necessary)