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Editorial

# Special Issue "Multi-Agent Systems": Editorial

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**Abstract:** Multi-agent systems (MAS) are built around the central notions of agents, interaction, and environment. Agents are autonomous computational entities able to pro-actively pursue goals, and re-actively adapt to environment change. In doing so, they leverage on their social and situated capabilities: interacting with peers, and perceiving/acting on the environment. The relevance of MAS is steadily growing as they are extensively and increasingly used to model, simulate, and build heterogeneous systems across many different application scenarios and business domains, ranging from logistics to social sciences, from robotics to supply chain, and more. The reason behind such a widespread and diverse adoption lies in MAS great expressive power in modeling and actually supporting operational execution of a variety of systems demanding decentralized computations, reasoning skills, and adaptiveness to change, which are a perfect fit for MAS central notions introduced above. This special issue gathers 11 contributions sampling the many diverse advancements that are currently ongoing in the MAS field.

**Keywords:** multi-agent systems; agent-based modeling; agent-based simulation; decision support

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## 1. Introduction

As intelligent systems pervade more and more our everyday life, the need for a coherent set of abstractions and technical tools to support their design, development, and maintenance keeps growing steadily. Multi-agent systems (MAS) nowadays represent the richest and most reliable source for such abstractions, given that they provide the components (the agents) to encapsulate essential features such as cognition and autonomy, as well as the notions required to put systems together (agent societies) and make them work in the real world (MAS environment) [1]. In addition, a few decades of intensive academic and industrial research on MAS, and their integration with the most recent advances in AI techniques and IoT technologies, have promoted the intense development and widespread diffusion of novel agent-oriented techniques, methods, and tools, and paved the way towards the acceptance of MAS as the forthcoming industrial mainstream for complex yet reliable intelligent systems.

Yet, the articulation of the MAS scenario is nowadays so overwhelming that the transition is going to make both researchers and practitioners busy for two more decades, at least—before all aspects and issues concerning MAS techniques and methods are fully understood and addressed within the many relevant application scenarios where MAS are required to operate. Providing a platform where MAS researchers can share their most novel and exciting findings and results is then crucial to support and promote the development and spreading of new MAS models and technologies: this is in fact the main motivation behind the special issue.

## 2. Overview

Before delving into the individual contributions gathered, a few general statistics and observations are useful to have an overview of the content and outreach of this special issue:

- 53 papers have been submitted for peer review, out of which 11 were finally published, resulting in an acceptance rate of $\approx$ 21%;
- the average time to publish, intended as the time passed from submission to online availability, is 41 days, with a standard deviation of $\approx$ 16 days—dates are publicly available on each paper web page, accessible from the special issue home page (https://www.mdpi.com/journal/applsci/special_issues/Multi-Agent_Systems_2019, last accessed 21 March);
- papers already generated an average of 538 downloads ($\approx$281 standard deviation)—we deem citations not worth considering yet, after just (less then) 1 year since publication;
- published papers have been co-authored by authors coming from 10 different countries, covering Europe, Asia, North and South America. Amongst these, Italy and China are the most represented, having 2 papers with more than one local author.

These numbers are in line with previous edition of the special issue [2], except for a lower acceptance rate, which reflects the more selective review process meant to increase the quality of the special issue and its potential impact on research and practice.

Figure 1 shows the wordcloud generated from the full text of the published papers.

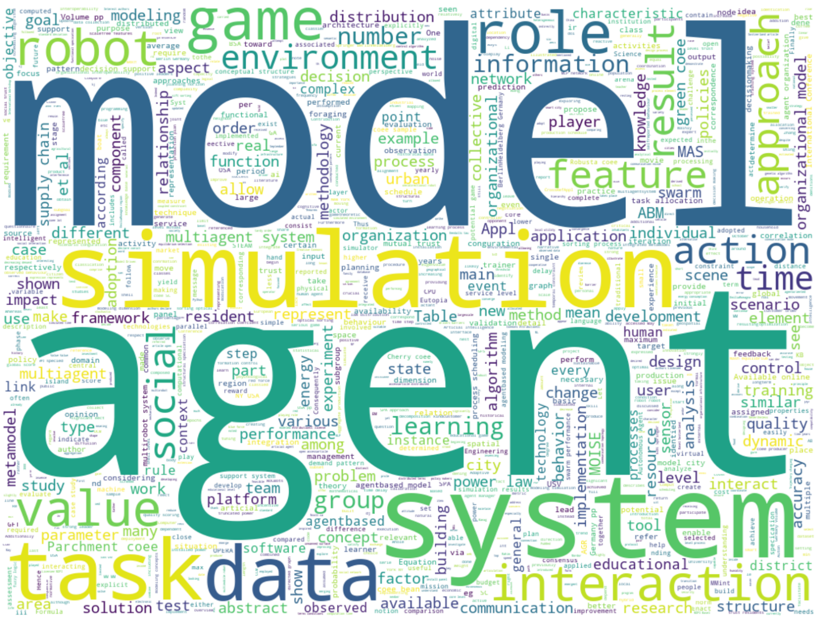


**Figure 1.** Wordcloud generated from the full text of each publication of the special issue.

The most mentioned words are "agent" and "model", closely followed by "simulation" and "system", and then by "task" and "data". The former four words are not surprising and confirm our editorial for previous edition: MAS are well-known and widely adopted also outside the strict boundaries of computer science and engineering exactly for the purpose of modeling and simulating complex systems, in fields as diverse as bioinformatics, social sciences, network science, supply chain, and logistics. The latter two words may instead appear as rather novel, and point to the increasingly widespread exploitation of MAS for novel purposes, such as collecting, managing, and analyzing data to turn it into actionable knowledge, and support execution of tasks requiring peculiar capabilities such as reasoning, reactiveness to environmental conditions, compliance to complex inter-dependencies.

Other highly relevant words working as clues for relevant application areas and kind of systems are the following ones:

- “game”, “role”, “social”, and “interaction”, which point to the social dimension of agenthood;
- “robot”, “environment”, “action”, and “time”, which emphasize the situated dimension of MAS.

In our previous editorial we analyzed a similar wordcloud from the perspective of the topics that were subject of the publications, which were: agent-based modeling and simulation, situated systems, socio-technical systems, and semantic technologies. Except for the latter, relevance of the other is confirmed by the current edition. That said, this year we would like to take a different point of view, by answering the following question: what are MAS used for? In the following sections we classify the papers included in this special issue according to the following four usage destinations, and summarize their main contributions:

*Decision support*—papers gathered in this category exploit MAS, in particular their ability to perform distributed reasoning, to deliver insights about a certain topic, with the goal of enhancing humans’ decision making processes and lower their cognitive overhead.

*Modeling framework and methodology*—in this category, what matters the most is the expressive power of the agent abstraction as a conceptual tool supporting engineering of complex systems featuring autonomous components.

*Programming abstraction and simulation framework*—complementary to the previous category, in this one MAS are mostly used for their operational features, as a software tool enabling development and execution of the complex systems already mentioned, especially in simulated scenarios.

*Execution infrastructure*—here, MAS are used as the backbone infrastructure executing the computations demanded by the application at hand, leveraging MAS themselves as an efficient and effective distributed computing platform.

## 3. MAS for Decision Support

Interestingly enough, the category reflecting the new entry w.r.t. previous editorial is also the most represented: 4 papers out of the 11 published exploit MAS to deliver decision support.

In [3], the authors exploit agent-based modeling and simulation to define a photovoltaic adoption prediction model based on self-reported behavior, then refined by a genetic algorithm looking at observed data. The goal is to help energy-related decision making by policy makers, by modeling and predicting households pondering whether to adopt photovoltaic energy solutions. Here, the agent abstraction is useful to model individual behavior driven by rational utility functions (such as economic savings), and the social dimension stemming from neighborhoods influencing each others’ decisions.

In [4], an MAS is used as the operational backbone of a game-theoretic approach to task allocation under strict spatio-temporal constraints, applicable to deliver decision support in many critical scenarios such as disaster relief. Here the main motivation behind usage of an MAS lies in the preference of quickness over optimality as regards convergence to useful allocations, as the targeted scenarios do not mind optimal solutions if they do not come within a reasonable time. As such, an MAS is built to run a scheduling algorithm rooted in game theory in a decentralized fashion, improving convergence time while giving away optimality.

In [5], an MAS is proposed as a platform for instrumenting a collective of neural network based classifiers by adopting a crowdsourcing metaphor: each classifier is an agent, each classification is an opinion, and the overall prediction delivered by the system is the aggregation of the crowd’s opinions. The goal is to improve prediction accuracy and transparency, by letting agents interact socially to exchange knowledge (e.g., new features), gain reciprocal trust, and change opinion when given enough evidence. The agent abstraction is then used mostly for its autonomy, and the MAS as an enabler of the sociality needed to improve transparency and accuracy through the exchange of information.

In [6], the authors target the green coffee supply chain with an agent-based decision support system devoted to planning production scheduling in face of fluctuating and peak demand. The modeled supply chain is rather complex, with plenty of interdependencies amongst activities and variables influencing the decision process at each step. An MAS is thus used to tame this complexity, by modeling all the different tasks and processes as autonomous agents, each undergoing its own reasoning to take decisions, while interacting with others upon need.

In spite of the heterogeneity of the application domains and the techniques adopted, all the described approaches leverage on MAS central notions to improve delivering of decision support functionalities, either by simulation [3,4] or as an operational platform [5,6].

## 4. Agent-Based Modeling and Methodology

As witnessed by the following papers, modeling complex systems of any sort within heterogeneous scientific disciplines is a staple in MAS application, either for observing such systems to devise out properties, patterns, and laws, or for crafting them in compliance with agent-oriented methodologies so as to obtain MAS non-functional properties—decentralization, reactiveness to change, etc.

In [7], an MAS is used in the context of social sciences to model residents in a smart city so as to study their social engagement during time (e.g., daylife vs. nightlife) and across space (city center vs. business district). The idea behind such a modeling is that activity of the residents are influenced by what others are doing and by environmental conditions, such as the presence of shops, events, etc., hence the social and situated nature of agents in an MAS is a perfect fit. Based on this modeling, the authors study various aspects of social and institutional engagement, such as mutual trust and trust in institutions.

The application context of [8] is instead totally different, as it deals with observation of emergent properties, in particular scale-free features, for robotic systems implementing swarming behaviors, such as collective foraging. The authors aim at testing whether scale-free attributes may also arise in artificial collective systems inspired to biological ones, such as ant colonies, and then whether such attributes have positive influence on the overall system performance. In such a context, the agent abstraction is particularly useful while modeling individual behavior of robots, which depends on environmental conditions (situatedness) and peers actions (sociality).

In [9], we are introduced to yet another research field exploiting the expressive power of the agent abstraction for modeling, while also considering a methodological perspective: psychology, in particular, educational games design. The authors describe a design process for educational games which heavily relies on the agent abstraction for modeling both human behavior and the software system engaging players, for instance, the admissible actions at each stage of the game, their effect on the system or the player(s), and the modalities of interaction between players and with the software control system. To further consolidate the agent metaphor, the authors also consider virtual avatars representing players and system characters, so as to leverage on more natural interactions.

## 5. Agent-Oriented Programming and Simulation

Complementing the modeling aspect discussed in previous section, the two following works exploit agent-oriented programming to deliver software tools enabling design and deployment of MAS and agent-based simulations.

In [10], a model-driven approach is proposed to reconcile all the different existing organizational models meant to let MAS designers operationally define the social dimension in an MAS. Organizational models respond to the need of guaranteeing correctness of the overall MAS behavior despite individual agents are autonomous entities, hence, as such, are able to choose their own course of actions in isolation—and while pursuing their own individual goals. Through these models and the corresponding software tools, MAS designers have ways of specifying co-operation protocols amongst agents, taming their individual behaviors and steering them towards a coherent system-level goal.

In [11], the focus of the contribution and the main novelty regard seamless deployment on simulated and production environments, with little modifications as possible to the agent logic. The authors propose a coherent and integrated Python development framework encompassing testing, simulation, validation, and deployment software production stages, as well as autonomy, reactiveness to environment events, and social ability facets of an MAS. The proposed framework, ARPS, revolves around a few crucial architectural components: the agent manager, agents themselves, a discovery service, and a discrete events simulator. Facilities for dealing with sensing and actuating in either simulated or physical environments are made available, and agent behavior as well as social interactions can be defined through policies dictating which actions correspond to which event.

Both the aforementioned contributions aim at providing general-purpose agent-based solutions to let other developers build their own MAS.

## 6. MAS as Execution Infrastructure

The last usage destination—that is, exploiting an MAS as the execution infrastructure for a given system—is quite common in MAS literature, as the agent abstraction is a general-purpose programming concept with applications in many business domains and for heterogeneous systems.

In [12], an MAS is used in the context of multi-robot formation: first, a distributed consensus algorithm is simulated on a multi-agent based simulation software to assess desired properties despite uncertainty of data and delay in communications, then such algorithm is implemented as an MAS and deployed on a real robotic platform comprising four mobile robots, further assessing effectiveness. In this work, the value added of the MAS lies in its natural predisposition to distribution and tight coupling with environment sensing and actuation, which are necessary features of multi-robot systems.

In [13], instead, an MAS is used as the platform for training unmanned surface vehicles: agents in the MAS correspond to vehicles' controllers and implement a distributed learning algorithm meant to achieve optimal coordinated behavior. Here, the agent abstraction is chosen for its capability to express adaptive behavior by learning new behavioral rules (likewise plans in BDI architectures) while operating.

Both contributions showcase the ability of MAS architectures to provide a suitable infrastructure for effective and efficient execution of heterogeneous tasks (consensus in the former, learning in the latter).

## 7. Conclusions

The large number of submissions to this second installment of the MAS special issue has made it clear that there is still a huge space that initiatives of this sort can help covering. In addition, the quality of the papers collected and published here testifies the effort that the scientific community is devoting to the development of novel MAS models, techniques, and methods. The breadth of the MAS-related topics faced by submitted papers (which for obvious reasons cannot be fully analyzed here) also witness the increasingly expanding reach of agent-based techniques and solutions.

This is mostly why this special issue on the one hand provides readers with a very representative picture of the state-of-the-art of MAS research, on the other hand is far from being conclusive under any possible viewpoint. The articulation and expansion of the MAS field leave the space open for many other initiatives like this special issue—so we expect to see many more of them in the next few years.

In the meanwhile, we are quite confident that the readers of Applied Intelligence will be able to understand the extent of the application scenarios that MAS are going to cover in the next decades, as they become the conceptual and technical foundation for the next generation of complex intelligent systems.

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