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# Special Issue "Multi-Agent Systems": Editorial

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**Abstract:** Multi-agent systems (MAS) allow and promote the development of distributed and intelligent applications in complex and dynamic environments. Applications of this kind have a crucial role in our everyday life, as witnessed by the broad range of domains they are deployed to—such as manufacturing, management sciences, e-commerce, biotechnology, etc. Despite heterogeneity, those domains share common requirements such as autonomy, structured interaction, mobility, and openness—which are well suited for MAS. Therein, in fact, goal-oriented processes can enter and leave the system dynamically and interact with each other according to structured protocols. This special issue gathers 17 contributions spanning from agent-based modelling and simulation to applications of MAS in situated and socio-technical systems.

**Keywords:** multi-agent systems; agent-based modelling; agent-based simulation; agent-oriented technologies; coordination; Artificial Intelligence; computer science

## 1. Introduction

Social, political, and technological pressure towards intelligent systems able to help and support humans in any non-trivial process and activity is leading the way for new programming paradigms, providing suitable abstractions and mechanisms for modelling and designing complex software systems. More the twenty years of academic research on multi-agent systems (MAS) have promoted agent-oriented models and technologies as the most suitable candidates for the design and development of distributed and intelligent applications in complex and dynamic environments.

To actually become "the next big thing", however, MAS need to complete their transition from a (mostly) academic product to the industry mainstream. To this end, a huge number of aspects and issues relating to MAS techniques and methods have to be scrutinised and explored within the many relevant application scenarios where complex intelligent systems are required: this is one of the main motivations behind the special issue.

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:

- 55 papers have been submitted for peer review, out of which 17 were finally published, resulting in an acceptance rate of ≈31%
- the median article processing time to publish, intended as the time passed from submission to online availability, is 40 days, with a standard deviation of ≈17 days—dates are publicly available on the special issue web page (https://www.mdpi.com/journal/applsci/special_issues/Multi-Agent_Systems)
- papers generated an average of 0.76 citations (1.71 standard deviation) and ≈687 downloads (≈326 standard deviation) per year—citations, downloads, and also views count are publicly available on each paper own web page, accessible starting from the special issue one

- published papers have been co-authored by authors coming from 13 countries, covering Europe, Asia, and South America. Among these, Spain is the most represented, having 5 papers with at least one local author

When considering that this is the first year of the special issue, and that Applied Sciences is relatively new to the field of research in agent-oriented models and technologies, we are very happy with both the number of submissions and their quality, as well as with the number and quality of the papers finally published. After their publication, papers are typically valued by the number of citations they get; obviously, they need a bit more time than less than a year to start generating mentions. Nevertheless, some of the papers published here have already started gaining attention.

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

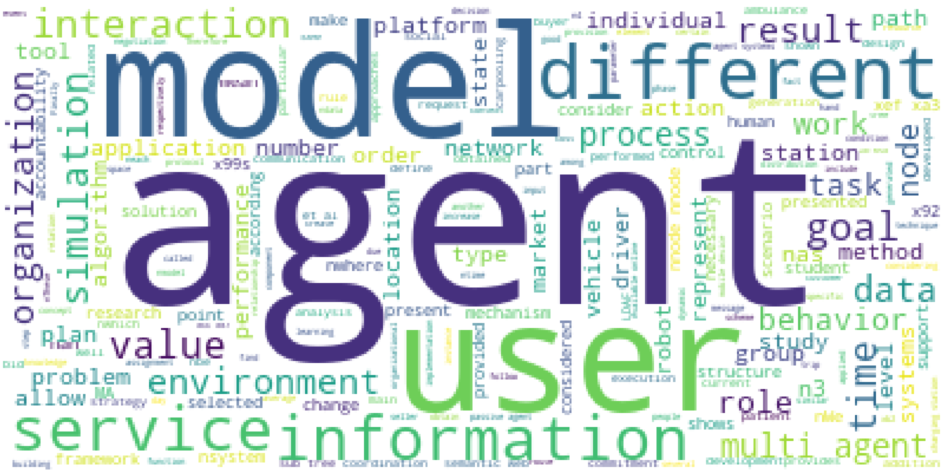


**Figure 1.** Wordcloud generated from the PDFs of each publication of the special issue (Python code available on request).

Unsurprisingly, the most mentioned word is "agent", followed by "model" and "user". The latter one may have a quite generic meaning, thus is difficult to interpretate, but the second one already highlights one of the relevant areas of application of MAS, that is, agent and multi-agent based modelling—which is one of the four main topics emerging from the analysis of the content of the published papers. Other highly mentioned words working as clues for relevant application areas are the following ones, presented along with our interpretation:

- "organisation", "role", which point to the *social dimension* of agenthood
- "simulation", which complements agent-based modelling with agent and multi-agent based simulation
- "environment", "time", which emphasise the *situated dimension* of MAS

Accordingly, in fact, the four main topics we identified by examining the content of the papers are:

**agent-based modelling and simulation** — as the disciplines of modelling systems by adopting the agent abstraction [1], possibly along the other two pillars of MAS—that is, environment and society—and of simulating systems as an ensemble of loosely-coupled, goal-oriented autonomous entities (indeed, agents), either competing or collaborating by exchanging messages

**situated systems** — as the application of agent-oriented models and technologies to systems highly intertwined with their environment [2], be it virtual or physical, there including the space-time fabric, hence leveraging the situated nature of agents' actions, which are deeply dependant on the context of performance [3]

**socio-technical systems** — as the application of agent-oriented models and technologies to those kind of systems where humans play a fundamental role, where they are (also) a functional part of the system itself, bearing with them all the complexities of human behaviour, organisational structures, ethical issues, cognitive aspects, etc. [4]

**semantic technologies** — as the discipline of making computational devices able to interpret and understand the semantics of objects, concepts, processes, etc., usually in the context of the Semantic Web vision [5].

In the following sections we classify published papers according to the categories above, and summarise their main contributions.

## 2. Agent-Based Modelling and Simulation

In [6] the authors apply *genetic programming* techniques to an agent-based model of training, education, and entertainment applications with the aim of automatically generating *agent behaviour trees*. By acknowledging shortcomings of genetic programming application to evolve behaviour trees—such as search space explosion and intensive knowledge engineering efforts—they complement the approach with both static and dynamic constraints to ease exploration of the search space while still being fairly domain-independent. To demonstrate efficacy of the proposal, they experiment with behaviour generation for the Pac-man game, achieving better behaviour in fewer evolutionary rounds w.r.t. other state-of-art approaches. As a bonus, they also get more readable behaviour specifications, suitable to be later refined by domain experts.

In [7] the author applies agent-based simulation to achieve fair purchase prices in the context of perishable goods markets. They aim at reforming the current market model, in which sellers are penalised by the rapid perishing of their goods (i.e., fish and vegetables) which forces them to accept buyers offers sooner or later—otherwise the goods will be wasted. To overcome this issue, they propose a *double auction model* in which buyers are penalised each time they fail an offer, so as to promote fair bidding prices. By simulating traders in different market conditions they show that their approach achieves fair prices for the allocation of goods.

In [8] the authors developed an agent-based *simulation software tool* to investigate how *students' sociograms*—a representation of social relationships—evolve during time. It has been demonstrated, in fact, that different sociograms contribute in different ways to the academic performance of students, thus arranging classes and lectures so as to promote such sociograms would be beneficial. Nevertheless, knowing the sociogram beforehand—before the education period starts—is not possible. The authors' work overcomes this limitation by enabling educators to simulate student sociograms as an agent-based model built out of students' psychological profile. The authors corroborate the hypothesis that simulated sociograms are sufficiently close to real ones through statistical binomial testing.

In [9] the authors propose TELEKA, an *agent-based model and architecture* for *network traffic* analysis and optimisation. The model is intended to exploit *negotiation* techniques to advance network management practices towards the fifth level of IBM's degree of automaticity in network management [10], which fosters network policies and goals able to autonomously adapt to the contingencies arising during operation. The proposed architecture is vertically decomposed in three layers: the lower one is in charge of fine-grained monitoring and low-level control of individual devices, the middle one is devoted to classify and aggregate perceptions coming from the monitoring so as to deliver higher level information to the decision making module, that is, the upper level of the architecture, in charge of triggering the SEHA negotiation algorithm for congestion resolution and traffic optimisation based on information and alerts coming from the lower levels. Effectiveness of the model is evaluated through simulations in NetLogo (https://ccl.northwestern.edu/netlogo/), and an analysis of sensitivity to different topologies is included.

In [11] the author formally investigates the problem of reaching consensus in presence of either transmission or processing delays. In particular, they focus on *scaled consensus*, where consensus is not about reaching agreement on an absolute common value, but rather about achieving given relative proportions [12]. They prove that scaled consensus can be achieved regardless of transmission delays as long as the network contains a spanning tree, whereas the same does not hold in presence of processing delays, which can hinder convergence to consensus when too large. In case consensus is reached, the scaled consensus values are the same regardless of the delays being due to transmission or processing. Numeric simulations confirm these formal results.

**Wrap up.** Despite their huge heterogeneity, all the research works just described perfectly sum up the circumstances that call for agent-based modelling and simulation: whenever the system under study is *decentralised* and *open* to dynamic join and leave of participants, who must be modelled as *autonomous* and *loosely* coupled entities (that is, related by soft dependencies), the agent abstraction is the way to go.

## 3. Situated Systems

In [13] the authors approach the problem of *coordinated control* of a fleet of autonomous hovercrafts at both the individual and the collective level: for the former, they propose a controller based on a Radial Basis Function Neural Network for tolerating non-modelled terms while following a given path, for the latter they apply *multi-agent consensus* to achieve movement in a desired formation. Simulations of the approach confirm effectiveness in a few selected communication topologies, such as cascade-directed communication graph and parallel-directed communication graph.

In [14] the authors apply *multi-agent based modelling* to the domain of *urban planning*, in particular, for supporting decision making about the design and deployment of an electric charging stations infrastructure in a city. The proposed multi-agent system features several agents in charge of complementary functionalities, such as querying open data portals of local administrations to gather info about potential offer and demand for charging stations as well as average traffic conditions, crawling social networks to rank potential locations where to put charging stations, and execute optimisation algorithms to find the best spots among a set of candidates. A graphical interface is also available to set various parameters guiding the optimisation process, which is based on *genetic algorithms*. The authors validate their approach with a case study implemented in the city of Valencia, Spain.

Also [15] concerns the domain of urban planning: there, the authors propose a multi-agent system providing decision support, in the form of *demand prediction services*, in the context of a *bike sharing* application. The system analyses heterogeneous data such as availability of bikes at stations, trip information, and weather forecasts to build a demand prediction model and a dashboard for historical data visualisation. The prediction model is built by comparing regression techniques such as Random Forest and Gradient Boosting, evaluated by means of the Root Mean Square Logarithmic Error. The resulting system has been deployed to the city of Salamanca, Spain.

In [16] the authors exploit *agent-based modelling* and simulation techniques to investigate how different agent behaviours and interactions affect the *negotiation process* in a car-pooling scenario. The proposed multi-agent system adopts an organisational metaphor to arrange and analyse the social relationships and individual behaviour of agents; in particular, the *Capacity, Role, Interaction, and Organization* meta-model [17]. The proposed system works in three main phases: *exploration*, during which agents search the carpooling social network seeking for opportunities to carpool, either as drivers or passengers, and get matched depending on user profiles, trip data, time of constraints, etc.; *negotiation*, where agents being matched start a negotiation process to fine-tune the details of the joint voyage, such as the actual departure time, the path to be followed, and the driver; *carpooling*, where the actual trip takes place and contingencies should be handled (such as disbanding non-compliant agents). To validate the approach, the FEATHERS operative activity-based traffic demand model is used to generate synthetic data and agents in order to test different negotiation settings.

In [18] the authors propose a novel *navigational strategy* for moving robots able to avoid collision with multiple passive agents featuring a (at most) partially predictable behaviour. The main application scenario envisioned is safe autonomous driving in presence of pedestrians, and the approach proposed—featuring a detailed kinodynamic model for the robot—is compared with acceleration-velocity obstacles [19] and generalised velocity obstacles [20] to showcase its gain in performance.

**Wrap up.** Also in this category papers tend to vary a lot in the actual topic of their contribution, yet they all adhere to a common principle: there are properties of the *environment* that the MAS is modelling, or within which the MAS is executing, which affect its functionalities, thus must be properly modelled. Be it the unpredictable oscillations of the physical environment—as in the case of the former and latter papers—or the need to account for spatial constraints while simulating a urban infrastructure, there are properties *outside of agents' control* that they should sense in order to proceed to decision making in an informed way.

## 4. Socio-Technical Systems

In [21] the authors argue that multi-agent systems featuring *agreement technologies* for coordinating agents' interactions are a good fit for many socio-technical systems in the common realm of *smart cities*. The motivation for considering agreement technologies stems from the *open* nature of most applications therein, when users may join and leave the system anytime, and whose behaviour is at most *partially controllable* and predictable—in contrast with software-only systems. They substantiate their claim with several use cases including intersection management, emergency evacuation, and healthcare, each accompanied with experimental results coming from either extensive simulations or actual deployments.

In [22] the authors develop a *personal assistant* agent leveraging and complementing ambient intelligence systems to safely navigate people with *cognitive disabilities* in unfamiliar environments. The proposed system features location tracking, an orientation system, and speculative reasoning to enable monitoring of patients' locations by caregivers and relatives, increase autonomy of patients, and pro-actively detect potential mistakes leading to the patient getting lost. Also, the proposed solution exploits a learning module based on past trajectories mining to build and keep updated a patient profile of familiar and preferred routes. Finally, to ease usage and understanding while lowering the cognitive workload of users, the system is served through an *augmented reality* interface which overlays crucial information on the physical world by means of a mobile device (such as a smartphone or tablet).

In [23] the authors target socio-technical systems where *accountability* of actions is a must-have feature. They propose a framework specific for multi-agent systems—named ADOPT—where accountability is enabled by the notion of *social commitment* [24], and can be enforced by design through a specific interaction protocol leveraging a shared environment and the notion of *role*—played by agents in a MAS organisation. In particular, a two-stages protocol is adopted, and defined as a sequence of two FIPA Contract-Net protocols [25]: in the first one, the role played by an agent while joining a computational organisation is established, while in the second one, the goals to pursue are negotiated. The proposed framework is then implemented on top of the JaCaMo agent development platform [26], featuring BDI agents programmed in Jason [27] and environment engineering based on CArtAgO artefacts [28], and conceptually validated in a toy scenario about an ensemble of agents cooperating to build a house.

In [29] the authors deploy agents in an interactive museum exhibit scenario, with the task of evaluating *interaction levels* [30] (the quality of interaction, frequency, average time, etc.) and improving user experience. In particular, three distinct agent sub-systems are designed: one representing the users, hence visitors attending the exhibit, thus modelling their behaviour and interactions with the museum facilities, one representing the interactive exhibits, and the latter implementing the self-evaluation functionality—delivered through a fuzzy inference system. Results of deployment of the MAS in practice are also shown, regarding 500 users visiting the "El Trompo" interactive museum in Tijuana, Mexico.

In [31] the authors used agent-based modelling for the *3D simulation* of work environments, with the goal of investigating potential accessibility problems w.r.t. people with disabilities. In particular, a multi-agent system has been developed in JADE [32] and integrated with Unity3D game engine, leveraging its 3D modelling capabilities, to enable *interactive simulations* for "what-if" analyses of potential architectural barriers. The overall system is thus, essentially, a decision support tool for Human Resources management offices. Accordingly, evaluation of the system is done against Indra Sistemas S.A. offices in Salamanca, Spain.

**Wrap up.** The lesson learnt here is that, unsurprisingly, the agent abstraction is a perfect fit for either modelling human behaviour or effectively deal with human users: for the former, *goal-orientation, autonomy, structured communication* capabilities, even *mental attitudes* if we consider BDI-like architectures [33], are all facets that characterise humans and that agents are able to mimic (at least, to some extent); for the latter, the same agents' abilities are useful to give human users a more natural peer for their interactions with technology.

## 5. Semantic Technologies

In [34] the authors build a novel *agent development platform* explicitly focussed on enabling development of *linked data* [35] aware agents, and deployment of mobile devices such as smartphones. In reference to the former feature, it implies that agents are able to gather information from a linked data graph, and store it in their own belief base, where it can be used to trigger execution of plans. Indeed, agents adopt the *BDI architecture* for inner reasoning, and *FIPA compliant* speech acts for communicating with others—FIPA standards are also adopted for the agent management functionality, thus the proposed platform features typical services such as white and yellow pages for, respectively, agents and services discovery. The proposed development platform has been evaluated in a toy scenario concerning an auction for exchanging products in an electronic market.

In [36] the authors propose a *model-driven development* platform and methodology for MAS, rooted in the domain-specific language *SEA_ML*, featuring BDI agents and *automatic code generation*, and specifically targeted at developing *Semantic Web* enabled agents. The platform is able to generate actual source code for JADE [32], JADEX [37], and JACK [38], thanks to a pipeline of model-to-model plus model-to-code transformations, as well as OWL-S [38] and WSMO [39] documents. SEA_ML meta-model and methodology articulates along 8 different aspects called "viewpoints": Internal for agents' inner behaviour, Interaction for their communication, MAS for organisational properties, Role for access control, Environment for handling of resources, Plan for plan actions and tasks definition, Ontology for knowledge specification, Agent–SWS Interaction for definition of entities and relations for handling Semantic Web Services.

**Wrap up.** This category is less represented and possibly describes a narrow area of application for agent-oriented techniques. Nevertheless, there is an important aspect that links semantic technologies with agents: intelligence. One acceptance of the term implies the ability to understand the *meaning* of concepts, not solely how to manipulate them. That is, one of the many possible interpretation of the term "intelligence" requires agents to understand what they are doing, what information they are communicating, etc., not only how to do so without any clue on the semantics behind actions and data. Under this perspective, semantic technologies are a great complement to agents' innate rational capabilities.

## 6. Conclusions

For both their quality and range, the papers in this special issue already represent a meaningful sample of the most recent advancements in the field of agent-oriented models and technologies. In fact, it is surprising to witness how such a limited portion of MAS research already highlights the most relevant usage of agent-based models and technologies, as well as their most appreciated characteristics. For instance, modelling and simulation straightforwardly substantiate our opening claim that agent-oriented abstractions are widely recognised as the most rich and useful for conceiving and designing complex systems, while situatedness directly puts MAS in relation with the dynamic and unpredictable nature of the physical environment.

We are then confident that the readers of Applied Intelligence will be able to understand the growing role that MAS are going to play in the design and development of the next generation of complex intelligent systems. Yet, the large number of submissions to this first instalment of the MAS special issue have made it clear that there is a huge space that could be covered by another special issue of the same sort. This is why the special issue has been converted to a yearly series, of which the new call is already available at the publisher website: https://www.mdpi.com/journal/applsci/special_issues/Multi-Agent_Systems_2019.

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