

Advancing Urban Science with Multi-Agent Systems: Prospects for Innovation and Sustainability in Spatial Planning and Urban Governance

Dario Esposito(✉) and Miriam Ruggiero

Polytechnic University of Bari, 70126 Bari, Italy
dario.esposito@poliba.it

Abstract. The paper explores the potential of Multi-Agent Systems (MAS) to enhance urban and regional planning. It provides background on the importance of understanding the complex and dynamic nature of cities and the limitations of established planning methods, which struggle to meet the increasing demands for improved quality of life and address social and environmental challenges. Through a comparative analysis of relevant studies, the paper illustrates how MAS can overcome the limitations of purely technical-operational application by providing a more comprehensive conceptualization, understanding, and decision-making in the anthropized environment. Despite the need for multidisciplinary teams and effective integration into the planning process, MAS can challenge partial viewpoints, ineffective decision-making, and implementation approaches. Moreover, MAS can inform public policies and support more efficient and equitable planning processes by assisting decision-makers in developing paradigmatic reasonings. Consequently, MAS can aid in designing innovative possibilities that are more sustainable and resilient by mirroring the complex interactions among individuals, organizations, and systems within territories and the communities that inhabit them. Ultimately, the paper highlights new perspectives for urban science inspired by the multi-agent methodology, emphasizing the advantages it offers in recognizing distinctive relational qualities within complex socio-technical ecosystems, enhancing understanding of the dynamic process of territorialization, and contributing to the cultural advancement needed for revitalizing the spatial planning discipline and guiding policymaking towards strategic perspectives.

Keywords: Multi-Agent Systems · Agent-Based Modelling · Spatial Planning · Urban Governance · Urban Science

1 Introduction

The anthropized environment is a multidimensional socio-technical ecosystem that is complex, open, and dynamic. With the systemic increase in the quantity and diversity of interaction of its constituent elements such an ecosystem becomes increasingly complex, giving rise to emergent properties that are qualitatively new. These properties

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Gervasi et al. (Eds.): ICCSA 2023 Workshops, LNCS 14109, pp. 368–384, 2023.
https://doi.org/10.1007/978-3-031-37120-2_24

allow complex systems to develop innovations, recognize and exploit new resources, and reorganize the network of agents to embrace change. Thus, enabling them to adapt or transform to overcome cyclical instabilities, unexpected crises and to reach new states of dynamic equilibrium (Meena et al. 2023).

For human civilization, culture and scientific knowledge are key to enabling this evolutionary mechanism, which ensures the persistence of society. Ecological and community dynamics including temporal fluctuations in species population is a consequence of the information processing (Ushio et al. 2021). However, knowledge in complex socio-technical ecosystems is also emergent and divergent future scenarios grows exponentially with time, making it difficult to accurately predict outcomes. Quoting Zadeh: "As the complexity of a system increase, our ability to make precise and yet significant statement about its behaviour diminishes until a threshold is reached beyond which precision and significance become almost mutually exclusive characteristics" (Zadeh 1996). Therefore, communities shaping and shaped by their living environment cannot fully anticipate the impacts of innovations.

Cities serve as the connecting medium for human communities. In this place agents live, produce knowledge, organize and form institutions (Glaeser 2011). Thus, they are the pivotal factor in understanding and orienting cities. This to the extent that their sustainable and innovative potential depends on the cognitive reach of their agents and the density of form and structure of the network of relations and interactions between them, which allows for certain social and spatial behaviours, but not others. Urban communities are composed of numerous agents who interact with one another, organize themselves into social networks, and make decisions about how to operate in the territory. Each agent makes decisions based on their partial knowledge, and these decisions, when implemented, can change the local context. The complex set of decisions and actions taken by all agents influences the organization of the entire system, resulting in emergent phenomena at the macro-level that are more than the sum of lower-level actions and provide feedback to individual agents, inducing adaptation at the micro-level.

Understanding this tripartite framework of complex multilevel and nested systems, formed by cities, communities, and knowledge, is critical to addressing challenges such as environmental and climate change in a sustainable manner. However, the uncertainties of domain knowledge and the plurality of perspectives and values underlying them, despite being not only unavoidable features, but also required aspects of the diversity that ensure innovation, present significant challenges to conventional linear approaches to spatial planning and urban governance.

The human component in spatial analysis introduces multiple and highly variable meanings, in terms of cultures, traditions, roles, and capacities that challenge those who study the territory to justify decisions supporting government choices. However, if the planning approach in practice is distant from reality and incapable of achieving desired effects, it is due to the clash between increasingly strategic objectives and the limitations of the methods adopted to study and govern the territory, affecting decisions at all levels. These limitations hinder the possibility of concretely realizing what has been imagined and postulated in line with the core principles and values of the discipline, such as democracy, equity, justice and sustainability.

Indeed, experts face the paradox whereby they believe they can shape and exploit the tools at their disposal to justify their point of view, but they remain trapped of the limitations of such tools and the organizational and regulatory frameworks within which they can be used. Consequently, the possibilities for effective change remain confined within narrow spatial and temporal perspectives. The ordinary approach is static and linear, following a knowledge path from data acquisition to analysis through information processing algorithms, to the explicit representation of results for decision support, which are often implemented through a series of hierarchical plans and sequential and controllable interventions, in the hope of reaching a compromise of interests and ends that is ameliorative (Porqueddu 2018). However, this process harshly reveals its precariousness when applied to study and manage complex and dynamic systems that are nonlinear, far from equilibrium, and unpredictable (Batty 2009) and where top-down imposition of decisions will likely produce unexpected and unintended consequences that generate problems more challenging than the issues they were intended to address (Lovins 1995).

Evidently, because the object of urban policies is such a complex socio-technical ecosystem, there is a need to go beyond the collection and analysis of data to try to discover the mechanisms that generated them. Thus, to move from data to meanings and new knowledge it is essential to refer to a paradigm capable of capturing flows of interactions, internal and external to the system, of the multitude of cognitive agents that generated those data. Indeed, there is a growing recognition of the need to rethink the traditional urban planning paradigm based on linear and deterministic models, with a more flexible, adaptive, and interactive approach, capable of embracing the complexity and uncertainty of urban systems. The multi-agent systems (MAS) approach offers interesting possibilities in this direction and can provide the preconditions for developing broader and more informed reflections for the renewal of the fundamentals of the discipline. The potential of MAS for urban planning has been recognized in a growing body of literature that has explored their use for a range of applications, such as transportation, land use, environmental management, and social simulation. However, most of these studies have focused on technical and operational aspects of MAS, without exploring their broader theoretical implications for urban science and spatial governance.

This research aims to explore the potential of MAS to update spatial planning theory and practice towards more strategic and participatory perspectives. The approach's flexibility can adapt to structure multiple spatial issues, situations, and phenomena, such as wicked problems and better represent the dynamic relationships between components characterizing the territory (Rittel and Webber 1973). Nevertheless, usually policymakers dismiss academic research as too theoretical, unrelated to the actual problems they are wrestling with, or in other ways irrelevant to their concerns (Gilbert 2002). The difference in perspectives poses an immediate difficulty in identifying a direct correspondence of the results obtained with the multi-agent analyses and the technical-design requirements, regulatory constraints, etc., that are the languages of applied urban planning. For this reason, the approach is often exploited only limitedly in circumscribed areas of research and case studies and is generally underutilized. Whereas considering the growing inadequacy of the discipline and the crisis due to the gap between values, competencies and real possibilities of impacting at both environmental and social levels,

MAS could lead the renewal of the conceptual paradigm of spatial governance and help to pursue strategic planning.

The study is guided by the following research questions: (i) What are the advantages of the agent-based approach for recognizing distinctive relational qualities in complex socio-technical ecosystems? (ii) What opportunities does it offer for a better understanding of the dynamic process of territorialization? (iii) What is its contribution to the cultural advancement needed to renew from the ground up the discipline of spatial governance and innovate policymaking toward strategic perspectives?

Hence, this research offers insights into how the use of the MAS approach for the understanding of phenomena from the bottom-up is not only beneficial for improving outcomes in various application contexts but also crucial for fostering an innovative approach to how spatial planning is conceptualized, implemented, and assessed. Additionally, these reflections demonstrate how MAS offers a new perspective on urban science, emphasizing the importance of cultural advancement in spatial planning and strategic policymaking.

The remaining of the article is organized as follows. Section 2 provides a background on theoretical foundation of MAS. Section 3 present a review of the case studies form literature on the use of MAS for spatial planning and urban governance. Section 4 discusses implications for urban science and spatial governance, illustrating the potential of MAS for addressing the research questions. Section 5 concludes the article by summarizing the main contributions and implications of the research, as well as its limitations and future directions.

2 Background

The dynamics of socio-technical ecosystems are too complex to understand analytically by studying the overall effects of phenomena, while a problem that is difficult to describe globally with hypotheses that cannot be proven mathematically can be described locally from the individual participating entities and through the operation of the MAS the emergent systemic effects can be captured. Definitely, by appropriately calibrate the simulated model, MAS can help answer questions about the dynamics of the real system.

Multi-agent systems (MAS) originated in computer science and engineering to model and simulate complex, distributed phenomena that occur in the real world and involve living systems characterized by different levels of intelligence and/or coupled with artificial intelligence. Thus, a MAS is a system of multiple agents that interact in a common environment and modify themselves and the environment. This cyclically and dynamically impacts and transforms the activities and behaviours of the agents that populate it. MAS is a broader term that encompasses the design and implementation of multi-agent systems, while agent-based modelling (ABM) specifically refers to modelling complex systems using a bottom-up, agent-based approach.

In ABM, each individual in the system is modelled as an autonomous decision-making entity with a set of properties, and action capabilities. Then several agents relate, communicate and interact autonomously in a shared, virtually represented environment and the system behaviour emerges from multiple local interactions. Agents with different characteristics, capabilities, and decision-making logic, starting from any initial

conditions and constraints, make autonomous and adaptive decisions, can improve their performance learning from experience, and act consistently to solve problems and pursue individual goals, but also can coordinate to achieve common or collective goals. Agents can be anything: animals, cities, nations, organisms, humans, businesses, organizations, institutions, and any other entity for which at least one purpose can be recognized or attributed. The environment can be described as an agent rather than as the background where agents operate.

MAS are used for understanding how the emergent behaviours of complex systems is related to the characteristics and behaviours of individual components and vice versa. For Railsback and Grimm, this is a cross-sectional and transcalar approach, simultaneously representing both what happens to the system because of what the agents do and what happens to the agents because of what the system does, as well as reciprocal influences between these levels (Railsback and Grimm 2019).

MAS are widely used for modelling and simulation of complex adaptive systems. It helps to capture when individual behaviour, ranging from reactive or proactive and from finalistic to conscious, produces the best outcome for the individual agent or for the entire community of agents, e.g. maximizing personal utility, improving the quality of life or safeguarding non-renewable resources. It is used to model social behaviour with game theory, to study the conditions under which mutualism and cooperation can emerge in a competitive social system. It figures out how to provide agents with adequate decision flexibility to readily change behaviour, so that they can adapt as needed to others and the environment to solve problems and overcome states of crisis. Moreover, MAS are useful for studying the effect of hypothetical external impacts on the overall development of the system. For instance, they can help understand the local response to unexpected global phenomena or assess the impact of high-level decisions on operational actions. An interesting case is the one of the spread of infections in an environment, which can help decision-makers in evaluating alternative measures and determining the most appropriate ones, such as assessing whether closing schools or cancelling flights is sufficiently effective in curbing the spread (Esposito et al. 2020a).

However, MAS has not only to do with specific quantitative conditions that must be met for some dynamic of interest to emerge, e.g. prerequisites and thresholds for something to activate or happen in the system according to if-then type logic. They are also used to understand how certain preconditions and critical quantities, through phase transitions, can lead to the spontaneous emergence of novel desirable qualities and properties in the system, or to identify dangerous tipping points toward which the system needs to be restrained (Rockström 2009). Thus, a MAS simulates the system of interest to capture its behaviour that is not necessarily an optimal strategy to reach an equilibrium, but rather a flexible process capable of producing a novel systemic change that can lead to discover a new dynamic equilibrium.

Although the multi-agent approach is still underutilized in town and regional planning compared to its real potential, according to this logic it is possible to use MAS to define the best policy for many different and varied decision-making scenarios. The present contribution evaluates the potential and limitations of MAS for the analysis and management of land and local communities through the identification of the methodology's peculiar characteristics, which are discussed with the analysis of example cases

and the evaluation of the advantages of their application in a paradigmatic dimension and with respect to the cross-cutting and dynamic qualities and beyond their specific purposes. In the following section, starting with the study of a range of relevant applications for decision support, a comparative analysis of the features of greatest interest for spatial planning strategies and urban governance is proposed.

3 Agent-Based Modelling in Spatial Planning and Urban Governance

Agent-based modelling (ABM) has become an important tool for the study of cities and regions. ABM enables the modelling of individual and social decisions and interactions that drive spatial dynamics, making it useful for decision-making, design, and management of urban systems and infrastructure. Indeed, ABM has been applied to understand the relationship between humans and space, ranging from the micro-movements of pedestrians to the growth of cities (Crooks et al. 2021).

ABM applications can simulate scenarios that consider the spatial perception and social and physical interaction capabilities of agents, and accurately foresee how the system will function, even during disasters (Esposito et al. 2021). These have been used to represent specific human and group behaviours, such as the emergence of crowds, evacuation in emergencies, pedestrian flows, vehicular traffic, and crowding. ABM have also been used to test hypotheses on topics such as wayfinding, queue formation, territoriality, conflict, and emotional contagion.

In spatial analysis applications, agents are endowed with capabilities for decision, action and movement, which are more or less simplified. The possibility to represent the location of agents and their context is crucial to replicate human spatial behaviour together with the decision-making process that drives it and as it is influenced by the characteristics of the surrounding environment through affordances (Golledge 2003), functions that enables certain activities and because of the presence of other agents (Gehl 1987).

To validate ABM, it is possible to modify rules, parameters and conditions in order to compare results of simulated dynamics with data collected in reality. ABM simulations of specific situations are developed with many agents expressing approximately linear behaviour, limiting the need to introduce assumptions about variability due to different cognitive abilities or social preferences, cases that are more difficult to validate. However, a few assumptions applied to many agents can generate complex and counterintuitive macro-phenomena, giving rise to unexpected outcomes that constitute the factor of greatest interest in the study of socio-technical ecosystems with ABM. Although many models still assume that agents have perfect spatial knowledge and can optimize their choices, a promising route forward could be to develop behaviour-based intelligence that allows agents to learn their environment for themselves and develop cognitive frameworks within the modelling package.

Table 1. Relevant features of illustrative use cases for different types of applications.

Subject	Time scale	Spatial scale	Agent capacities	Environmental role	Types of agents	Number of agents	Type of space	Reference	Application
Pedestrian movement	minutes	neighbourhood	reactive		pedestrians	100 000		Rose et al. (2014)	pedestrian flow in the city centre
Migration	months	regions	reactive	background	groups	22 millions	geographic	Groen et al. (2017)	effect of conflicts
Evacuation	minutes	city	reactive coordinated	active background	pedestrians buildings	37 000	geographic	Iskandar et al. (2020)	earthquake
Evacuation	minutes	city	reactive cooperative	active	pedestrians vehicles	40 000	grid topologico	Aguilar, Lalith (2016)	earthquake tsunami
Crowd safety	hours	neighbourhood	reactive proactive	background active	pedestrians	260 000	grid	Batty (2003)	crowding at events
Crime	hours	city	proactive	background active	buildings individuals and groups	273	geographic	Malleson (2012)	crimes and residential burglaries
Public health	days	city	reactive reflexive		individuals	1000	geographic	Perez, Dragicevic (2009)	spread of diseases
Disasters	minutes	neighbourhood	reactive		groups	1000		Barnes et al. (2021)	study of behaviour
Housing market	months	city	reactive		individuals bank	1,6 millions		Geanakoplos et al.(2014)	real estate bubble
Traffic	minutes	neighbourhood			vehicles	15 000	geographic	Manley, Cheng (2018)	traffic flow forecast

(*continued*)

Table 1. (*continued*)

Subject	Time scale	Spatial scale	Agent capacities	Environmental role	Types of agents	Number of agents	Type of space	Reference	Application
Land use changes	years	city	motivated proactive	background	territory areas		grid	Liu et al. (2013)	urbanisation of rural settlements
Spread of diseases	hours	building	reactive motivated	background active	individuals	50	geographic	Esposito et al. (2020b)	contamination and contagion
Energy demand	months	regions		background	Individuals groups	households housing drives	geographic	Muñoz H. (2016)	energy requirements for heating
Urban growth	years	city	reactive	background	groups	1668 slums	geographic grid	Patel et al. (2018)	formation of slums

Some MAS applications of interest with reference to typical use cases drawn from the literature are taken up and elaborated upon below in a non-exhaustive guideline list. Table 1 provides schematic details of selected example applications of ABM, with classification of the most prominent features and reference to the research from which they are taken. Specifically, the definition of the type of space follows the taxonomy proposed by Macal and North (2014) and Crooks et al. (2018), the one relating to agent capability refers to the classification proposed by Weiss (1999) and Gershenson (2001), and the role of the environment is alternatively evaluated as a background with the mere function of a physical constraint or as an active element able of influencing agents states, capabilities or choices.

Table 2. Problems, limits and advantages of using MAS for each type of application.

Subject	Problem	Limits	Advantages
Pedestrian movement	include pedestrians' spatial preference for exploring city streets and places in the model	need to simplify complexity with assumptions about preferences such as time budgets, routes, destination, etc. for each agent	the model allows the testing of various scenarios, even hypothetical ones
Migration of populations	predicting the distribution of refugees fleeing as involuntary migration	much more time is needed to develop the model than the rapid response required by the crisis	it is possible to predict the distribution of refugees in destination camps
Emergency evacuation	include human behaviour and the anthropogenic impact it has on the disaster	need to consider actions taken during and immediately after a disaster event	social behaviour can be simulated, which is the key to security
Crowd safety	merging a traditional processing model with a dynamic model	complexity is given by the unpredictable stimuli in the agents' movements	testing alternative routes to reduce crowding
Crime	capture the bottom-up dynamics of the criminal system like human behaviour	irrational behaviour and complex psychology lead to computational difficulty	captures emerging phenomena related to interactions between individuals and space
Public health spread of diseases	the spatial effects of diffusion, the individual contact process and the effects of individual behaviour are ignored	computational limitation; the simulation does not take prevention measures into account	increases the flexibility of the model; subdivision by age, gender, etc.; simulate any other communicable diseases by modifying the time line and the transmission process

(*continued*)

Table 2. (*continued*)

Subject	Problem	Limits	Advantages
Disasters	Not rely only on the routes given by emergency plans. Make sure that the agents do not all move in the same way	if we do not enter the characteristics of the agents we have a knock-on; not all complexity can be entered	inclusion of human behavioural characteristics (gender, age, mobility)
Housing market	including heterogeneity in real estate market variables	seasonality; lending constraints and boom characteristics; role of real estate, mortgage brokers, developers	excellent results in reproducing the data history; it is suitable for economic processes
Traffic	incorporate the results of cognitive science	it is not easy to capture the heterogeneity of driver behaviour	introduces both heterogeneous spatial knowledge and the choice of preferred route
Land use changes	incorporate agents' behaviour	only considers conversion from other types of land to communal land, and not vice versa	understanding of land development
Energy demand	use not only high-level aggregated data and capture the complexity	data at a low level of aggregation are difficult to obtain; calculation of domestic heating energy needs only	micro-scale representation and monthly resolution
Urban Growth	explore links between individuals and aggregated data	requires data that are very often not available in developing countries	predicting the location of slums and exploring the interactions between human behaviour, environment and policies

Table 2. Shows schematically for each type of application considered: the problem which the analysed study seeks to address, the advantages of using ABM for the specific case study, and any limitations encountered.

Figure 1. Represents the spatial, temporal, and quantitative dimensions of the types of applications considered.

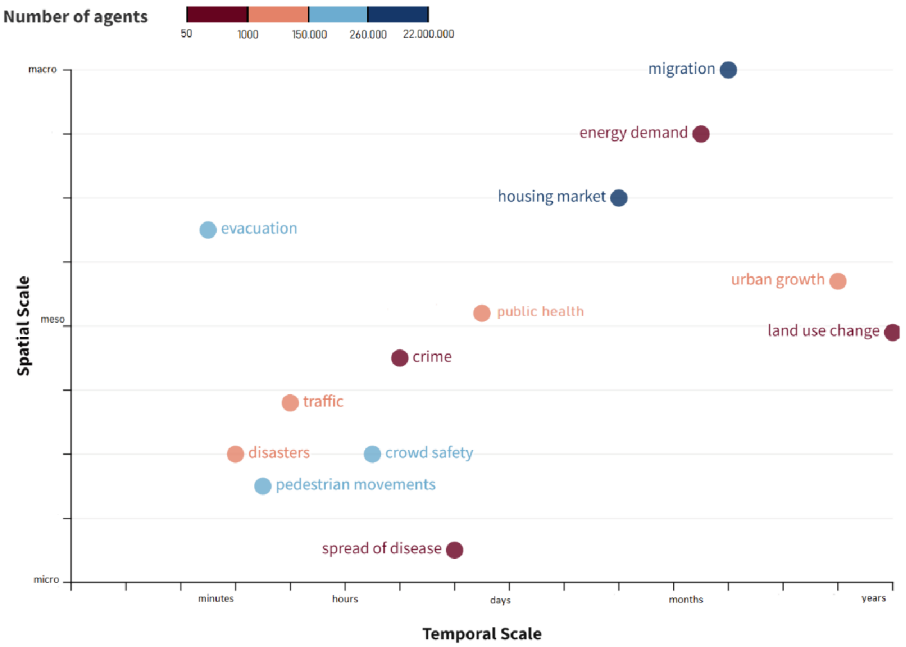

Fig. 1. Representative graph of the spatial, temporal, and dimensional dimensions of the various applications considered.

4 Discussion

Based on the case studies analysed, we can draw cross-cutting assessments of the potential and limitations of applying MAS for analysing and managing the land and man-made environment.

The complete development of a multi-agent model involves several steps, which can be condensed into three main stages in a cyclic process: (i) conceptual modelling of the phenomenon or problem to be analysed, (ii) computational simulation of what-if scenarios, and (iii) analysis of results to confirm or disprove assumptions and update the formulated model. However, it is not always necessary to go through all three stages. In fact, formalizing issues according to the logical architecture proposed by the MAS paradigm may be sufficient to significantly improve understanding (Esposito et al. 2020c).

Leveraging MAS main strength, which consists in recognizing the elements under study on the basis of the qualities derived from the relationships among them, offers experts an opportunity to rethink the established methods. Since these, still today, mostly look at static and intrinsic properties of the elements involved, such as physical-geometric characteristics and market values. Thus, ABM are not only useful for the specific purpose

for which they are built; they also allow us to examine organizations and the relationships between people and space.

While spatial planning is primarily concerned with the "where" (Abbott 2020)– i.e., norming, regulating, and deciding where to realize the infrastructure that society intends to build, and constraining geometric and dimensional aspects at most – the MAS approach forces us to consider "when" and "for how long." This has the great advantage of spurring us to think about what we intend to accomplish in terms of its implications for development, and to read spatial governance decisions as part of a dynamic and open-ended process of territorialization, both spatially and temporally. Through simulation in the virtual environment of the MAS, we can observe the mutual influences between these two levels. Being able to grasp and evaluate the effects of spatial choices in the temporal dimension is crucial to effectively manage any complex territorial living system. This is important for socio-technical ecosystems, as they structurally exploit scientific innovations and their technological applications to cyclically postpone the moment of systemic collapse (Bettencourt et al. 2007). From a broader perspective, given the increasingly frequent and dramatic emergencies predicted in the near future, being able to grasp the conditions and requirements imposed by the pace of change necessary to target societal adaptation for resilience can make all the difference in ensuring the survival of the human species on the planet. The possibility to model together different temporal and spatial scales is also crucial for urban-scale dynamics.

Furthermore, the MAS approach helps us think in terms of who is involved, since is inherently suited to considering active agents in the area and their characteristics, i.e. it forces us to recognize that these agents are not static, but change dynamically. Moreover, it allows us to capture the overall effects resulting from the decisions of many agents, which is beyond the rational capacity of an expert. From a problem-solving perspective, MAS help to identify adaptive solutions that take advantage of the natural and instinctive propensities and behaviors of agents of the systems, as well as the actual conditions offered by the environmental and cultural context. This is preferable to opposing these tendencies by proposing solutions. As is the case with the imposition of rules and constraints, that result inadequate. Moreover, because they allow agents of different types to be included within the same model and aggregated into phenomena that serve as the building blocks for higher-level or larger-scale complex systems at different scales, multilevel effects through nested systems can be represented simultaneously.

Additionally, the logic behind MAS allows for the focus of studies on the relationships between elements rather than solely on their intrinsic properties. In spatial and environmental issues, it is becoming increasingly evident that it is not essentially the nature of the agents or their properties that unite or differentiate them, but rather how they relate and interact with one another. In fact, even if the number of relationships increases exponentially with the number of agents involved, just a handful of agents can connect in hundreds of different ways. By paying attention to the connectivity among agents, we can examine a specific feature of the spatial complexity of environmental systems. The network of connections serves as an organization of interconnections among agents, and it is through this that agents continuously exchange flows of energy, goods, information, capital, waste, up to the point that choices and actions of one agent somehow influence

or have implications for another agent connected to the network, even at great distances (Batty 2013).

MAS allow us to abstract from the dimensionally measurable spatial instance alone and look at the complex system composed of the relationships among agents, which are organized into networks that give rise to spatial phenomena (Esposito and Abbattista 2020d). Indeed, ABM can also be designed in a way that agents connect through links and space is ignored, closing to network analysis. As the degree of connectivity between agents increases, it becomes more and more the quantity, nature, pattern, and properties of connections that define the system, rather than the properties of individuals. Once a critical level of connectivity among agents is reached, the system stops being a set of parts and becomes a single complex system, and its development depends on how things flow in the network.

This consideration is especially useful for complex systems that exhibit high levels of interdependence and is, therefore, of interest in dealing with the urgent and current problems peculiar to a globalized society in a highly connected world. The space of these complex systems, such as global systems of transportation, of people and exchange of goods, social networks, and the financial system, is redefined in terms of the topology created by connectivity that replaces the Euclidean conception of space. What matters in defining the importance, role, and development prospects of an agent in the network, as well as the territory it physically inhabits, is its position in the network structure and its degree of connectivity. This interpretation allows us to understand how the anthropic environment functions from the shape of the network and the relative position of each agent. For example, it enables us to identify key agents in the network who can leverage phenomena to activate change and assess the implications of a certain structure of the existing connection. Indeed, if an agent lives in a central node of the network, it will shape the context in which the agent exists and may have more or different information and possibilities, living in a very different world from those who inhabit the margins. Megacities, for instance, serve simultaneously as nodes of different types of global networks, whereas medium-sized cities may need to develop strategies to become access nodes of at least specialized global networks. Each city always acts as the place where global and local networks meet and serves as an access point for people to communicate and work with each other from there.

Lastly, it is important to underline that many agent-based models tend to look at only one aspect of a spatial system at the time. If we want to address larger societal issues, such as climate change or urban change, specific models need to be integrated to couple various processes together.

5 Conclusion

The paper examines how Multi-Agent Systems (MAS) can enhance urban and regional planning by addressing the limitations of traditional methods that struggle to manage the complex and dynamic nature of cities. It presents a comparative analysis of studies demonstrating how MAS can support decision-making by providing a more comprehensive conceptualization of the urban environment, as well how MAS can improve sustainability and resilience by understanding the interactions between individuals, organizations, and systems within communities.

The developed reflection is supported by an analysis of relevant cases, focusing on the characteristics, advantages, and limitations of applying Multi-Agent Systems (MAS) to urban and regional planning. Considerations allow us to define dimensions by which MAS can improve urban science, contributing to a more complete and accurate understanding and representation of the object of study and thus to a more effective governance of the territory. Indeed, ABM are a powerful tool that make it possible to simulate what-if scenarios to explore systems and processes they cannot directly manipulate and through which it is possible to improve understanding of the physical and social impact of the built environment on communities and vice versa. Emblematic is the case of worst-case scenarios, which are impossible to reproduce in the real environment because of the logistical, economic and safety implications of in vivo experiments. Best practices demonstrate that for policymakers, the use of these computational tools can be critical to the success of solutions and initiatives to plan and manage infrastructure, territories, and communities. MAS approach activate iterative processes in which alternative solutions and information obtained from the analysis of what-if scenarios are used to reason about and formulate new hypotheses to be tested. This is a dynamic and flexible process that aims to recursively minimize the gap between the unfolding reality and the expert assumptions made in adaptation to it.

They can support urban and spatial planning by simulating complex interactions between individuals, organizations, and systems within a city. Their flexibility means that it is the phenomena of interest that determine the most appropriate scale for representation, not the limitations of the methodology adopted for modeling. Thus, they can help planners predict and understand the impacts of different planning scenarios and policies, taking into account factors such as land use, transportation, demographics, and economics. By providing a virtual test bed for planning, these tools can support more informed, efficient, and equitable planning processes. This information can support decision making, help identify potential issues and conflicts, and evaluate effects and effectiveness of alternative policies.

Their challenge is to advance the level of knowledge of anthropogenic systems at all scales and to develop useful processes to support experts in dealing with the innate variability and uncertainty of socio-technical ecosystems. In terms of the connections between the technical-application aspects of the method and the implications at the theoretical level, the potential of MAS exceeds the expressive scope of simulations applied to solve contingent shorter-term technical management problems. Indeed, at the end of the analysis it is possible to detect a high degree of results variety with the introduction of small variations in the starting data, thus exactly mimicking what happens in complex socio-technical ecosystems for which small variations in the starting conditions to rapid divergences.

Rather than arriving at certain and reassuring predictions, MASs serve as flight simulators to train experts to deal with the unexpected by failing repeatedly in virtual mode, rather than when making choices in the real world. In fact, its greatest value lies in its ability to project those who use them onto a level of paradigmatic reasoning capable of challenging partial viewpoints and established ways of doing things. Making human systems sustainable, encouraging innovation in society, promoting community disaster resilience and a circular economy for better resource use, and many other issues, are

all largely dependent on a proper understanding and representation of decisions and interactions among agents in complex spatial systems. MASs are a metaphor by which it is possible to understand how simple things produce complex phenomena, in that they function not to offer a snapshot of the situation, but to capture the development of a dynamic process for which we have the instructions, but not the description of its development. MAS help decision-makers invent innovative perspectives that are more sustainable and resilient precisely because they are more adherent to the complex nature of territories and the communities that inhabit them.

Despite these envisaged benefits, the use of ABM tools may have limited impact if they are not integrated effectively into the broader planning process and if decision makers do not have the necessary technical skills to understand them. Only in rare cases is this methodology included in the planner's training, and thus multidisciplinary teams are needed for its implementation. This is also why ABM are not widely used and are hardly officially recognized in professional practice. As these tools become more accessible and user-friendly, they are likely to be adopted by a wider range of planners, stakeholders, and citizens and become increasingly integrated into the broader planning process, serving as a central tool for understanding, communicating, and evaluating.

Nowadays, typical evaluation of public policies is steadily based on a definition of a plan that can be easily tracked and measured upon indicator that are known a priori. This assumption leaves no room for socio-technical ecosystems that adapt, evolve and learn which are exactly what objects of public policies, such as the economy, the environment, the society and the cities. Indeed, spatial plans and projects based on norms and laws could be the strangest as long as they are justified by causes and preconditions and meet pre-established requirements, resources and budgets. In truth, objectives are easily lost in the face of the race to meet regulations and constraints on time. Therefore, they often offer no assurances on how clear and useful goals will be achieved fulfilled and who will be responsible for them, and people needs satisfied. Ultimately these are often self-referenced to meet the expectations of decision makers and therefore although they are very reassuring for them, at the same time they are not also effective for others in view of sustainability and innovation.

In contrast, strategy development has to do with a set of win-win choices that are also feasible because they analyse the agents involved and their network of relationships over time to achieve a clear end strictly related to the welfare of other agents, citizens and the environment for example, who are external to the decision maker and over whom the decision maker has no control or guarantee of success. In line with this wisdom, the MAS approach proves to be not only useful addressing specific technical-operational issues, as much as in creating conditions such that the decision maker can build informed visions, teaching him or her to think about the right questions to ask and why to ask them, and finally to develop the ability to make dynamic an flexible choices that can be readily modified in the process. All these issues are at the hedge for renewed strategic spatial planning and sustainable city and community governance.

6 Contribution

Conceptualization, methodology, writing and revision D.E.; figures and editing M.R. All authors read and approved the published version of the manuscript.

References

Abbott, C.: City planning: a very short introduction. Oxford University Press, USA (2020)

Aguilar, L., Lalith, M.: On a mass evacuation simulator with complex autonomous agents and applications. J. Earthquake Tsunami **10**(05), 1640021 (2016)

Barnes, B., Dunn, S., Pearson, C., Wilkinson, S.: Improving human behaviour in macroscale city evacuation agent-based simulation. Int. J. Disaster Risk Reduction **60**, 102289 (2021)

Batty, M.: Agent-based pedestrian modelling, Advanced spatial analysis: the CASA book of GIS **81**, 81–106 (2003)

Batty, M.: Cities as complex systems: scaling, interaction, networks, dynamics and urban morphologies (2009)

Batty, M.: The New Science of Cities, MIT Press, Cambridge (2013)

Bettencourt, L.M., Lobo, J., Helbing, D., Kühnert, C., West, G.B.: Growth, innovation, scaling, and the pace of life in cities. Proc. Natl. Acad. Sci. **104**(17), 7301–7306 (2007)

Crooks, A., Malleson N., Manley E., Heppenstall A.: Agent-based modelling and geographical information systems: a practical primer, Sage (2018)

Crooks, A., Heppenstall, A., Malleson, N., Manley, E.: Agent-based modeling and the city: a gallery of applications. In: Shi, W., Goodchild, M.F., Batty, M., Kwan, MP., Zhang, A. (eds.) Urban Informatics. The Urban Book Series. Springer, Singapore, pp. 885–910 (2021). https://doi.org/10.1007/978-981-15-8983-6_46

Esposito, D., Schaumann, D., Camarda, D., Kalay, Y.E.: Decision support systems based on multi-agent simulation for spatial design and management of a built environment: the case study of hospitals. In: Computational Science and Its Applications – ICCSA 2020a. ICCSA 2020a. LNCS, vol. 12251, pp. 340–351. Springer, Cham (2020a). https://doi.org/10.1007/978-3-030-58808-3_25

Esposito, D., Schaumann, D., Camarda, D., Kalay, Y.E.: Multi-agent modelling and simulation of hospital acquired infection propagation dynamics by contact transmission in hospital wards. In: International Conference on Practical Applications of Agents and Multi-Agent Systems, Springer. Cham, pp. 118–133 (2020b)

Esposito, D., Abbattista, I., Camarda, D.: A conceptual framework for agent-based modeling of human behavior in spatial design. In: Jezic, G., Chen-Burger, J., Kusek, M., Sperka, R., Howlett, R., Jain, L. (eds.) Agents and Multi-Agent Systems: Technologies and Applications 2020c. Smart Innovation, Systems and Technologies, vol. 186, pp. 187–198. Springer, Singapore (2020c). https://doi.org/10.1007/978-981-15-5764-4_17

Esposito, D., Abbattista, I.: Dynamic network visualization of space use patterns to support agent-based modelling for spatial design. In: Luo, Y. (ed.) Cooperative Design, Visualization, and Engineering. CDVE 2020d. LNCS, vol. 12341, pp. 260–269. Springer, Cham (2020d). https://doi.org/10.1007/978-3-030-60816-3_29

Esposito, D., Cantatore, E., Sonnessa, A.: A multi risk analysis for the planning, management and retrofit of cultural heritage in historic urban districts. In: La Rosa, D., Privitera, R. (eds.) Innovation in Urban and Regional Planning. INPUT 2021. LNCE, vol. 146, pp. 571–580. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-68824-0_61

Geanakoplos J., Axtell R., Farmer D., Howitt P.: An agent-based model of the housing market bubble in metropolitan Washington, DC (2014)

Gershenson, C.: Artificial societies of intelligent agents, Fundacion Arturo Rosenblueth Unpublished Thesis (2001)

Gehl, J.: Life between buildings, Van Nostrand Reinhold, New York, vol. 23 (1987)

Gilbert, N., Maltby, S., Asakawa, T.: Participatory simulations for developing scenarios in environmental resource management. In: Third workshop on agent-based simulation, pp. 67–72, SCS-European Publishing House, Ghent, Belgium, April 2002

Glaeser, E.: Triumph of the City: How Urban Spaces make us Human. Pan Macmillan (2011)
Golledge, R. G.: Human wayfinding and cognitive maps. In: The Colonization of Unfamiliar Landscapes, pp. 49–54. Routledge (2003)
Groen, D., Suleimenova, D., Bell, D.: Towards an automated framework for agent-based simulation of refugee movements. In: Winter Simulation Conference (WSC) (2017)
Iskandar, R., et al.: Agent-based simulation of pedestrians' earthquake evacuation; Application to Beirut, Lebanon (2020)
Liu, Y., Kong, X., Liu, Y., Chen, Y.: Simulating the conversion of rural settlements to town land based on multi-agent systems and cellular automata. PLoS ONE **8**(11), e79300 (2013)
Lovins, L.H., Lovins, A.: How not to parachute more cats. Rocky Mountain Institute, Snowmass, Colorado. Published online at www.rmi.org (1995)
Macal, C., North, M.: Introductory tutorial: agent-based modeling and simulation. In: Proceedings of the Winter Simulation Conference, pp. 6–20. IEEE (2014)
Malleson, N.: Using agent-based models to simulate crime. In: Heppenstall, A., Crooks, A., See, L., Batty, M. (eds.) Agent-Based Models of Geographical Systems, pp. 411–434. Springer, Dordrecht (2012). https://doi.org/10.1007/978-90-481-8927-4_19
Manley, E., Cheng, T.: Exploring the role of spatial cognition in predicting urban traffic flow through agent-based modelling. Transp. Res. Part A: Policy Pract. **109**, 14–23 (2018)
Meena, C., Hens, C., Acharyya, S., et al. Emergent stability in complex network dynamics. Nat. Phys. (2023). https://doi.org/10.1038/s41567-023-02020-8
Muñoz Hidalgo, M.E.: A national heat demand model for Germany. In: Namazi-Rad, MR., Padgham, L., Perez, P., Nagel, K., Bazzan, A. (eds.) Agent Based Modelling of Urban Systems. ABMUS 2016. LNCS, vol. 10051, pp. 172–188 (2017). Springer, Cham. https://doi.org/10.1007/978-3-319-51957-9_10
Patel, A., Crooks, A., Koizumi, N.: Spatial agent-based modeling to explore slum formation dynamics in Ahmedabad, India. In: Thill, J.C., Dragicevic, S. (eds.) GeoComputational Analysis and Modeling of Regional Systems. Advances in Geographic Information Science, pp. 121–141. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-59511-5_8
Perez, L., Dragicevic, S.: An agent-based approach for modeling dynamics of contagious disease spread. Int. J. Health Geogr. **8**(1), 1–17 (2009)
Porqueddu: Detecting and directing emergent urban systems. A multi-scale approach. Cosmos+ Taxis. Stud. Emergent Order Organ. **5**(3+ 4), 32–49 (2018)
Railsback S. F., Grimm V.: Agent-Based and Individual-Based Modeling: a Practical Introduction. Princeton University Press, Princeton (2019)
Rittel, H.W., Webber, M.M.: Dilemmas in a general theory of planning. Policy Sci. **4**(2), 155–169 (1973)
Rockström, J., et al.: Planetary boundaries: exploring the safe operating space for humanity. Ecol. Soc. **14**, 1–33 (2009)
Rose J., Ligtenberg A., Spek S. V. D.: Simulating pedestrians through the inner-city: an agent-based approach, Bellaterra, Cerdanyola del Vallès. In: Social Simulation Conference (2014)
Ushio, M., Watanabe, K., Fukuda, Y., Tokudome, Y., & Nakajima, K. (2021). Computational capability of ecological dynamics. bioRxiv, 2021–09
Weiss, G.: Multiagent Systems: a Modern Approach to Distributed Artificial Intelligence, MIT Press, Cambridge (1999)
Zadeh, L.A., Klir, G.J., Yuan, B.: Fuzzy Sets, Fuzzy Logic, and Fuzzy Systems: Selected Papers (vol. 6). World scientific (1996)