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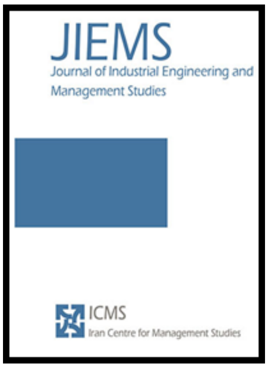

Complex adaptive systems, agent-based modeling and supply chain network management: A systematic literature review

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Abstract
In recent decades, researchers are turning to the potential of ABMs to study complex phenomena. Due to intrinsic interconnections, structural interactions and inter-dependencies, individual variations, and communications of various components, supply chain network should be accordingly treated as a complex adaptive system. ABM is dominant tool exploring the emergent behavior of supply chain network with numerous interactive agents. This paper aims to conduct a systematic literature review on the agent-based modeling in the concepts of supply chain and various fields of research. Using reputable databases, combining intended keywords and applying filters based on restrictions and indicators, a total of 123 relevant articles are selected from the valid journals and conferences in year 2010-2019, and 17 subjects in association with supply chain management and 23 subjects related to other fields are presented. Moreover, a brief history and the definition of the three basic areas including complex systems, complex adaptive system and agent-based modeling are provided. The main objective is to provide a perspective based on agent-based modeling and complex adaptive systems for researchers in different sciences and especially supply chain researchers, who are not sufficiently familiar with the philosophy and applications of these approaches.

Keywords: agent based modeling; complex adaptive system; supply chain network; systematic literature review.

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1. Introduction and background

In addition to remarkable progress in performing complicated and voluminous calculations through the advancement of computer software and variety of programming languages, and due to intrinsic interconnections, interactions, and communications of various components situated in time and space, simple models are losing their effectiveness and proficiency. Accordingly, scientists are seeking solutions for the problems with different levels of complexity. The need to create different scenarios by decision-makers has necessitated the

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existence of powerful tools such as Agent-Based Modeling and Simulation (ABMS). ABMS enables the modeling of decision-making entities including individual, heterogeneous, and autonomous agents (Bonabeau, 2002).

A primitive and effective step to build a powerful ABM is to recognize complexity, complex systems, and emergence subjects. Complex systems consist of diverse and numerous interactive parts. The complex systems approach seeks tools to peruse various real-world phenomena. The ABM is a powerful tool through which the characteristic of uncontrolled self-organization is understandable in some complex systems. The ABM considers complexity as a function of the agents and rules governing them as well as their interactions, at various levels from organizational and human to atomic. The highlight is that, development of complexity is a momentous prerequisite for verifying an agent-based model. To ease complexity, exploitation of software as well as coding is a way to adjust the complexity of ABMs.

Several methods are available to design ABMs. The decision to choose modeling method relates to several parameters, as following: the type of phenomenon that needs to be modeled, the amount of knowledge about intended phenomenon, and even the software or programming language to be used. Wilensky and Rand (2015) introduced two major categories of modeling: (a) phenomenon-based modeling and (b) exploratory-based modeling. In the first category, intending to have a reference pattern, the AB modeler begins with a reference phenomenon to obtain a set of agents and rules governing them in order to create a known reference pattern. In exploratory-based modeling, the AB modeler identifies emerging patterns by creating agents and defining their behaviors. In this method, the resemblances of proposed model with the concrete phenomenon ought to be represented.

Santa-Eulalia et al. (2011) provided a systematic literature review in the realm of developments methodological frameworks for the modeling and simulation of agent-based advanced supply chain planning systems. Their research covers agent-based supply chain planning systems in general terms, and the previous search to identify those works explicitly containing methodological aspects is specialized. Alrabghi and Tiwari (2015) addressed simulation-based optimization of maintenance by systematically classifying the published literature and outlining main trends in modeling and optimizing maintenance systems. based on their research, discrete event simulation (DES) was the most reported technique to model maintenance systems whereas modern optimization methods such as Genetic Algorithms was the most reported optimization method in the literature. In this research, they cite appropriately (Lynch et al., 2013; Tateyama et al., 2010; Triki et al., 2013; Fallah-Fini et al., 2010; Gupta and Lawsirirat, 2006), which are relevant to the field of research and agent-based simulation approach, Simultaneously. Van der Zee (2019) proposed a framework for simulation model simplification addressing the manufacturing field, thereby building on an extensive literature review.

This paper aims to identify the main recent advances in the domain of ABMS applications in SCM researches, in addition to subjects in association with supply chain management and other fields. In order to do so, a systematic approach is employed aiming to identify, select and make an analysis and a critical summary of all suitable studies dealing with presented research area. Due to the lack of recent reviews in the domain of CAS and ABM methodological frameworks for supply chain networks, the present paper contribution is to systematize and consolidate related works in last decade. Moreover, this study introduces interesting research gaps for future studies.

The remainder of this paper is as follows. Section 1 provides a brief overview on the philosophical background of the system, complexity and complex systems, as well as the need to utilize the ABM approach in researches based on such systems. Section 2 explains the mechanism and method of conducting our literary. After a concise reviewing on the selected researches focusing on experimental sciences and biology, energy, environment and greening, healthcare, MPC and POM, logistics, resilience and maintenance, Section 3 is devoted to representation of articles in supply chain area employing the ABM approach. Finally, section 4 presents the results and suggestions for future studies.

1.1. Finding the philosophical roots of system, complexity and complex systems

"Socrates," says Renan (The Life of Jesus, 1991, ch. 28) "gave philosophy to mankind, and Aristotle gave it science. There was philosophy before Socrates, and science before Aristotle; and since Socrates and since Aristotle, philosophy and science have made immense advances. But all has been built upon the foundation which they laid." Before Aristotle, science was in embryo; with him it was born. If philosophy is the quest of unity Aristotle deserves the high name that twenty centuries gave him —Ille Philosophies: The Philosopher" (Durant, 1926, p. 72). As stated by Callender (2007), "Philosophy was born when the early Greeks learned to view the world as a kosmos (cosmos), which was intelligible and hence controllable, in thought and rational action. One formulation of this cosmic order was the Aristotelian worldview with its holistic and teleological notions. Aristotle's idea that "the whole is more than the sum of its parts" is a definition of the basic system idea."

Durant coined the term *Aristotelian System*. This compound suggests a deep insight of Durant into the concepts of the system and Aristotelianism as the parts of key foundations of systemic thought. As stated in the *History of Philosophy* (Durant, 1926, p. 68), "…so man, in the Aristotelian system, is a rational animal, his "specific difference…" is that unlike all other animals he is rational." On the other hand, Aristotle pointed to the difficulty of defining the boundary between this kind of systems and their environment, called solids or death. He said, "… At the bottom of a scale, we can scarcely divide the living from the "dead"; "nature makes so gradual a transition from the inanimate to the animate kingdom that the boundary lines which separate them are indistinct and doubtful" (De Anvma, ii, 2.)…" and "that intelligence has progressed in correlation with complexity of structure and mobility of form (De Partibus Anvmaliurn, i, 7; ii, 10.)".

According to Mainzer (2007), "Complexity determines the spirit of twenty-first century science. The expansion of the universe, the evolution of life, and the globalization of human economies and societies all involve phase transitions of complex dynamical systems". In addition, He stated, "The theory of nonlinear complex systems has become a successful problem solving approach in the natural sciences – from laser physics, quantum chaos, and meteorology to molecular modeling in chemistry and computer assisted simulations of cellular growth in biology. On the other hand, the social sciences are recognizing that the main problems of mankind are global, complex, nonlinear, and often random, too. Local changes in the ecological, economic, or political system may cause a global crisis. Linear thinking and the belief that the whole is only the sum of its parts are evidently obsolete".

Distinctions between complexity and complex system as well as differences between complicated and complex systems are especially worthy of note. In complicated systems, inputs and their corresponding outputs are proportional to permanent solutions and controllability as well as separability into components. In contrast, relationships and the characteristics of self-organization, interrelationships, and evolution form the foundations of complex systems. Differences between complicated and complex systems from Poly (2013) point of view are shown in Table 1.

Table 1. Complicated systems vs. complex systems

	Complex systems	Complicated system
1	Work with open systems	Work with closed systems
2	Adopt a zero sum framework	Adopt a positive sum framework
3	Rely on first order systems	Include second order systems
4	Cognition through functional analysis	Cognition through structural analysis and division into smaller sections
5	Lack of direct connection with the amount of new data and knowledge	Understandable and able to be modeled through data collection and knowledge

1.2 Complex adaptive system, emergence and agent based modeling

Complex Adaptive Systems (CAS's) are generally called Open Dynamic Systems (ODS's) that self-organize their structural configuration through the exchange of information, energy, and other resources in their environment (Larson, 2016). By responding to multiple factors, complex adaptive systems could not be created or controlled by individual actors (Aagaard, 2012). In Aagaard (2012) point of view, fitness landscape, adaptive capability, integration, differentiation and fragmentation are the hallmarks of complex adaptive systems. A complex adaptive system is a system of individual agents, who are free to act in ways that are utterly unpredictable and whose actions are tightly interconnected such that one agent's actions change the context for other agents (Anderson et al., 2012). Interactive agents in a complex adaptive system follow rules, interact with local environment as well as global and change the environment to which they respond, according to their simple actions (Antonacopoulou and Chiva, 2007). This means that these types of systems can learn and adapt to changes in their environments (Bode and Wagner, 2015).

From network perspective, as Bovaird (2008) expressed, complex adaptive system resembles a network of agents operating in parallel, where control is very fragmented. In this kind of circumstances, the coherent behavior is due to competition as well as cooperation between the agents themselves. There are many organizational levels so that agents at one level serving as building blocks for higher-level agents and by gaining experience, revising, and continually changing the order of their constituent parts, implicit or explicit assumptions about the environment constantly tested by agents. In other words, complex adaptive systems are highly interconnected networks of semi-independent agents through which broad patterns of the system emerge, which could be learned and adapted over time (Davis et al., 2015). According to Larson (2016), CAS's are self-organizing systems and consequently, external forces have very little direct control over these systems. Continuous organic fundamental and structural interactions occur within and between such systems, and components learn to adapt to external forces. It means these systems are dynamic. Once systems have learned to adapt to their new environment, CAS tends to turn into new modes. In the literature of complexity this state is called "emergence". Honebein (2009) considered complex adaptive systems as emerging systems, meaning that they form and develop over time through an evolutionary process.

"Emergence" as a significant issue in the field of complex systems, relates to appearance of novel properties (from non-existence to existence). Aritua et al. (2009), Hunt et al. (2009), Hanseth and Lyytinen (2010), Lauser (2010), and Lindberg and Schneider (2013) consider emergence to be a tenet of complex adaptive systems. Chibbaro et al. (2014) believe that emergence and reduction are strongly related, and both relate to the unity or multiplicity of sciences and specific scientific theories seek to explain phenomena in terms of different disciplines and sub-fields. Since the eighteenth century, "emergence" has been used as a technical term in evolutionary physics, geology, and biology, where represents the appearance of a new and functional organ in a plant or animal line (Adler et al. 2002).

Kim (2000) has introduced the principles of the emergentism doctrine as follows:

1. Emergence of complex higher-level entities: Systems with a higher level of complexity emerge from the coming together of lower-level entities in new structural configurations.
2. Emergence of higher-level entities: all properties of higher-level entities arise from the lower-level properties and relations that characterize their constituents. Some properties of these higher, complex systems are “emergent”, and the rest merely “resultant”.
3. The unpredictability of emergent properties: emergent properties are not predictable from exhaustive information concerning their “basic conditions”. In contrast resultant properties are predictable from lower-level information.
4. The inexplicable/irreducibility of emergent properties: Emergent properties, unlike those that are merely resultant, are neither explicable nor reducible in terms of their basal conditions.
5. The causal efficacy of the emergency: Emergent properties have causal powers of their own; novel causal powers irreducible to the causal powers of their basal constituents.

Batterfield (2011) defined emergence as “properties or behavior of a system which are novel and robust relative to some appropriate comparison class.” Emergence as a controversial concept has a complex and interwoven background in science and philosophy. Scientists who have not achieved the desired results from a reductionist approach and have turned to holism and interactionism to find their responses (Piguliucci, 2014) have considered the idea of emergence. As ontology seeks the nature of everything, and epistemology depends on how one thinks and acquires knowledge of the nature of everything, one can look at the "emergence" of both ontological and epistemological approaches. While ontological claims are metaphysical, they are practical for epistemology (Piguliucci, 2014).

Descartes as a pre-Newtonian reductionist suggested that, in order to perceive any complex phenomenon, you have to decompose (reduce) it into individual components, and if still complicated, the procedure must repeat. Figure 1 indicates two types of interpretations of the reduction concept. In order to achieve unity and explain the phenomena in question, the philosophical view is to reduce specific theories to general. The physical view considers general theories with the inclusion of more specific theories. The reductionist materialist mechanistic or Newtonian worldview regarded the universe as a vast and complex mechanical system in which, components created a coherent whole according to repetitive and discoverable patterns (Callander, 2007) called Natural Laws. If it repeats largely to the smallest possible parts or the atoms (literally "indistinguishable"), what presently calls "elementary particles," will result in consideration of separate parts of matter. For this reason, Newtonian ontology is materialistic, because it assumes that all phenomena are ultimately composed of matter.

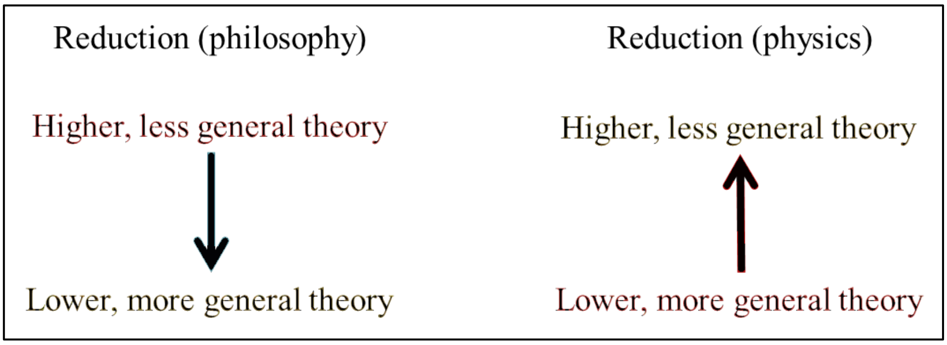

Figure 1. Two types of reductions (Chibbaro et al., 2014).

Newtonian science reveals five important properties about natural systems (Poly, 2013). Natural systems are:

1. Closed (only effective causality is accepted; bottom-up, top-down, "final" causes and prohibited);
2. Atomic (Fractionable);
3. Reversible (inherently without temporary direction);
4. Definite (Given sufficient information about the initial and boundary conditions, the future evolution of the system could be determined with any necessary care);
5. Universal (natural laws apply everywhere, at all times and on all scales).

While the Newtonian ontological elements of matter are the absolute space and time, through which matter moves, and forces or natural laws govern motion, Kant emphasizes on evolution. Kant believed that the universe has three basic parts: space, indivisible components (atoms), and the laws that govern them. Among these rules, dissolution of objects as well as evolution is very important. To confirm the argument, he quoted poems by Mawlawī, a famous Iranian poet (Durant, 1926, p. 113):

“No single thing abides, but all things flow.

Fragment to fragment dings; the things thus grow;

Until we know and name them. By degrees,

They melt, and are no more the things we know.”

Based on findings of Bishop and Atmanspacher (2006), it is a difficult way for reduction, obtaining the necessary and sufficient conditions to describe the characteristics of higher levels precisely on the basis of description of the properties for a certain level. Emergence is revealed, if the conditions for describing the properties of higher levels are necessary and insufficient, which in itself requires contingent contextual conditions. If the conditions for describing the properties of higher levels are unnecessary and sufficient, the description of the lower level offers multiple realization of a particular property at a higher level. Finally, if the conditions for describing the properties of higher levels are both unnecessary and insufficient, provided that there are no conditions for these two levels, a kind of radical emergence is proposed.

	Necessary	Not necessary
Sufficient	strictest possible form of reduction	supervenience
Not sufficient	emergence	radical emergence

Figure 2. Emergence matrix

According to Figure 2, the subject of ‘Supervenience’ was able to gain a philosophical position in 1970 by Davidson. The main idea of Supervenience is that "mental characteristics may depend on physical properties, while physical characteristics could not be reduced." As

Zuck (2015) stated “By talking about mental properties that ‘supervene’ on physical properties it was possible to give expression to a form of dependence, which was akin to causal dependence, but avoided the reduction of mental properties to physical effects or causes.”
Based on Mittelstrass (2014) the reductionist view is to simplify the structure of complexity by creating a model. As a rule, a distinction must be made between scale models, analog models, and theoretical models. Expansion or miniature scale models are real or imaginary objects. Analog models show one object in another object in terms of a similar structure (homomorphic). Theoretical models include a set of assumptions and equations that could be used to understand the basic properties of an object or system.
Todays, researchers are turning to the potential of ABMs to produce unbalanced results and complex phenomena. These results often involve self-organization or emergence. Self-organization involves creating a pattern or form from the bottom up. The formation of crystals and the complaint of birds are the classic examples of self-organized behavior. The term emergence is used for phenomena involving higher-order functions (de Marchi and Page, 2014). In many domains, ABM competes with Equation-Based Modeling (EBM) approaches that identify system variables and evaluate or integrate sets of equations relating these variables (Parunak et al., 1998). Both approaches simulate the system by constructing a model and executing it on a computer. For equation-based modeling, Goli and Davoodi (2018), Tirkolaee et al. (2019a, 2019b), Davoodi and Goli (2019) and Sajedinejad et al. (2020) deserve to be considered.
Emergence is the result of a local behavior and is integrated into the behavior of complex system (as a whole), while is separate from the origin, and details of its behavior are irrelevant to the outcomes of the whole system. Optical illusion pictures are good examples demonstrating different levels of emergence (each person can perceive different levels of emergence). As can be seen in the Figure 3, by changing the angle and distance of view of the picture, the lady’s portrait hidden between the black bars can be observed. It is possible to see her portrait only by having an overview of picture, and after that, each of the black and white stripes' details including all the patterns and drawings will not affect the overall perception.
In this regard, Miller and Page (2007) stated as following: “while this metaphor of emergence is very appealing, it leaves open the question of how it should fit into scientific discourse. Part of the innate appeal of emergence is the surprise it engenders on the part of the observer. Many of our most profound experiences of emergence come from those systems in which the local behavior seems so entirely disconnected from the resulting aggregate as to have arisen by magic, echoing Clarke’s observation about advanced technology”.

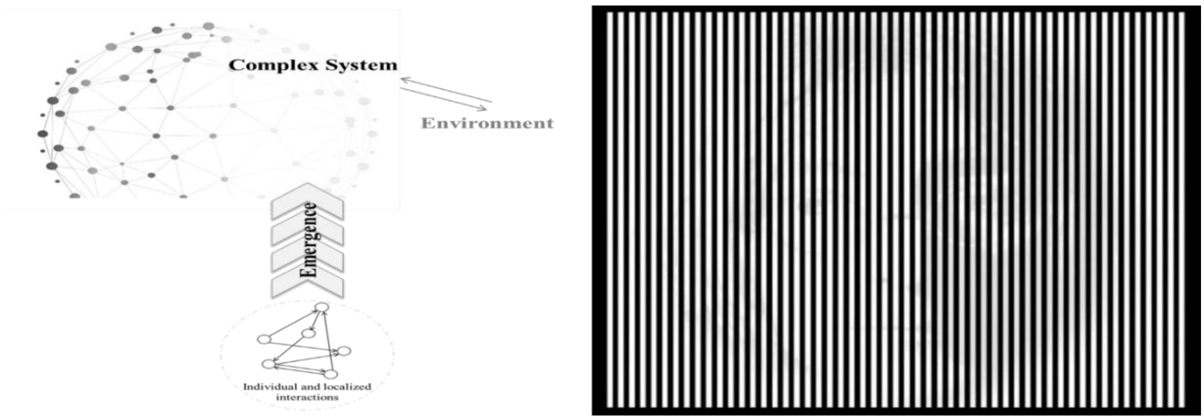

Figure 3. Optical illusion and emergence are as the result of a local behavior that integrated into the behavior of complex system

Agent-Based modeling consists of interactive and autonomous objects (agents) that situated in time and space (Holland and Miller, 1991). Since these types of models are computer-based, their behavior would be based on the rules. Agent-based modeling is a methodology employed to model by scientists in many disciplines (Kollman et al., 2003). De Marchi and Page (2014) discussed the agent-based modeling provides a way to uncover systems with interactive, adaptive, diverse, and localized actors. Equilibrium points, equilibrium distribution, cycles, randomness or complex patterns are the results of the agent-based models that arise from the interactions of model actors. These behaviors may range from rational and payoff-maximizing strategies to rules that mimic heuristics identified by cognitive science. Agent-based models have the potential to make progress in the social sciences and better understand complex systems.

De Marchi and Page (2014) also outlined some of the capabilities of the base operating models; They allow researchers to link behavioral rules to interconnected patterns through complex patterns (bottom-up), prepare micro-macro mapping and test the empirical validity of the results produced (Fowler and Laver 2008). They allow researchers to encrypt behaviors and understand how to integrate them. Possibility of geographical and social enclosure as well as networking at several levels of analysis, are others capabilities. ABMs can involve several processes. To learn the agents from the environment and from each other and subsequently, the behavioral details and more interactions leads to more cooperation between the agents. ABMs involve heterogeneity, not only in spatial location, beliefs, information, preferences, and abilities, but also in learning rules, perspectives, mental models, behavioral sets, and frameworks. As stated by Page (2006), “ABMs prove capable of producing messy contingent outcomes and a range of phenomena: randomness, equilibria both static and distributional, patterns and complexity, and the complex outcomes can vary in their amount and type of path dependence”. According to De Marchi and Page (2009), agent-based models make it possible to examine the neighborhood of models. Neighboring models can assume different behaviors from different network factors or topologies, and even place features in a network structure. They emphasize the robustness of the results. That is, can the system do what it needs to do?

2. Methodology

This systematic literature review (SLR) is conducted on the ABMS in the concept of supply chain management using the Science direct database and Google Scholar search engine and keywords' combinations. This article does not attempt to list all of the researches in the field of ABMS. In addition to examining the growing trend of using ABMS tools and also the sciences that use this approach as far as possible, the present paper seeks to indicate the importance of using ABMS in the supply chain management as well as industrial management and engineering. This approach makes researchers in other fields of science to consider the option of using the ABMS approach to solve their complex problems.

This paper aims to identify the existing potentials of ABMS in the development of various scientific fields and also complex problem solving approach in the field of supply chain networks. Using the intended databases in the second half of 2019, this SLR accomplished by identifying and selecting relevant papers to respond to the issues as following:

- Question 1: What specific fields do existing ABMS applications cover in complex adaptive systems?
- Question 2: What are the current developments of ABMS to solve complex supply chain network problems?
- Question 3: What are the potentials of ABMS for future studies?

Initially, a search string was provided for use in Science Direct and Google Solar databases. The Boolean expression "agent-based model" OR "agent-based simulation" OR "multi-agent model" OR "multi-agent simulation" OR "agent-based modeling and simulation" was determined in the first step based on the keywords in the field of ABMS. This work has been done in first step to identify the maximum research related to ABMS in various scientific fields. Then, according to Table 2, the published articles in the field of supply chain and ABMS are identified and reviewed by determining the Boolean expression: ("agent-based model*" OR "agent-based simulation" OR "multi-agent model" OR "multi-agent simulation" OR "agent-based modeling and simulation") AND "supply chain". The items presented in the results section are listed based on the content and order of the year of publication. Due to some limitations, 94 articles in the field of non-supply chain and 26 articles in the field of supply chain with a focus on ABMS have been reviewed. These articles have been selected by filtering 1116 articles in the first step and achieving 120 articles in the second step.

Table 2. Systematic process of selecting articles for analysis

First step	Boolean expression: "agent-based model" OR "agent-based simulation" OR "multi-agent model" OR "multi-agent simulation" OR "agent-based modeling and simulation"	
Number of results	Anywhere Title Abstract	7801 851 1831
Second step	In the title and keywords selected for more evaluations and duplicates elimination. Filter: • Articles that have not been able to access all of its content in any way. • Joint articles between selected databases. • Invalid conference papers.	
Number of results	1119 (table 2)	
Third step	Boolean expression: ("agent-based model*" OR "agent-based simulation" OR "multi-agent model" OR "multi-agent simulation" OR "agent-based modeling and simulation") AND "supply chain"	
Number of results	Anywhere Title Abstract	1036 10 80
Fourth step	In the title and keywords selected for more evaluations and duplicates between databases is eliminated. Filter: • Articles that have not been able to access all of its content in any way. • Joint articles between selected databases. • Invalid conference papers.	
Number of results	123	

Database: Science Direct Journals and JIEMS.
Search engine: Science Direct, Google Scholar and Google.
Data of search: The late first half of 2019.
The desired time period for online publishing articles: 2010-2019.
Type of documents: Articles, Review articles and Conference paper in English.
Search criteria: Agent-based.

In order to have a higher quality search, some general filtering has been developed. In terms of research language, English has been selected. In terms of the year of publication of the researches, the articles that were published in the years 2010 to 2019 have been selected. In terms of the type of research articles, review articles, valid conference papers and in terms of search field, abstracts, keywords and their titles have been assessed. In terms of content, the field in which the ABMS is used and the cause or causes of it, to some extent its software, the results obtained, definitions and characteristics are examined in more detail.

3. Results and description

As presented in Table 3, in the initial step of identifying target-related research, 1119 articles from 29 reputable journals were identified. Figure 3 depicts the frequency with which agent-based modeling and simulation are applied in research identified by each journal. Due to the constraints of the authors in terms of access to some non-free articles or lack of access to all the content of some articles as well as some other scientific considerations, 94 articles focusing on sciences that do not cover the supply chain and 28 articles in the field of chain Supply selected. The first category of articles was classified into 22 main areas, in which at least 3 articles and a maximum of 16 articles have been studied in detail. These areas are: Experimental sciences and biology, Water, Energy, Environment and greening, Food, Healthcare, Economy, Risk, Logistics (transportation, routing and traffic), Resilience, Manufacturing Planning Control (MPC) and Production and Operations Management (POM) and at the end Maintenance.

Table 3. Number of identified articles based on journal and per year of publication.

Name of Publication/ Year of Publication	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Total
Journal of Industrial Engineering and Management Studies								1		2	3
Science of The Total Environment				1	1			1	1	1	5
Bioorganic & Medicinal Chemistry	1		2				2		1		6
European Journal of Medicinal Chemistry		1		1		1	1	1		1	6
Research in Transportation Economics							1	2	1	3	7
Computers & Chemical Engineering	1			1	2		1	2		1	8
Renewable and Sustainable Energy Reviews						1	2	2	1	3	9
Decision Support Systems	1	1	2	1	1		1	1		2	10
Economic Modelling		1		1	1	1	2		2	2	10
Journal of Environmental Management	1			2		1	2			4	10
Journal of Theoretical Biology	2		3	1	1	1	1	2	1	1	13
Communications in Nonlinear Science and Numerical Simulation		1	2	2	3	1			1	6	16
European Journal of Operational Research			1	2	1	2	5	2	3		16
Future Generation Computer Systems		3		1			2	4	4	6	20
Energy Policy	5	2			3	1	2	5	2	2	22
Journal of Cleaner Production			1			1	2	7	3	8	22
Journal of Economic Dynamics and Control	1	1	1	2	2	5	3	4	3	3	25
Applied Energy			2	1	2	1	3	6	6	6	27
Applied Soft Computing	1	4	1	2	5	3	5	1	6	7	35
Computers, Environment and Urban Systems	4	4	5	4	3	2	6	6	2	9	45
Physica A: Statistical Mechanics and its Applications	2	1	6	6	4	3	5	4	12	6	49
Simulation Modelling Practice and Theory	3	2	5	2	6	4	1	4	15	8	50
Ecological Modelling	5	9	4	2	6	5	5	10	9	1	56
Environmental Modelling & Software	6	3	2	15	6	5	4	7	5	5	58
Transportation Research Part A to F	5	2	3	2	7	5	12	7	10	9	62
Information Sciences	3	1	4	6	7	5	13	5	17	8	69
Expert Systems with Applications	10	23	24	14	10	11	6	6	4	8	116
Energy	9	11	11	6	18	13	25	25	20	32	170
System	13	24	25	17	14	14	16	13	18	20	174
Sum											1119

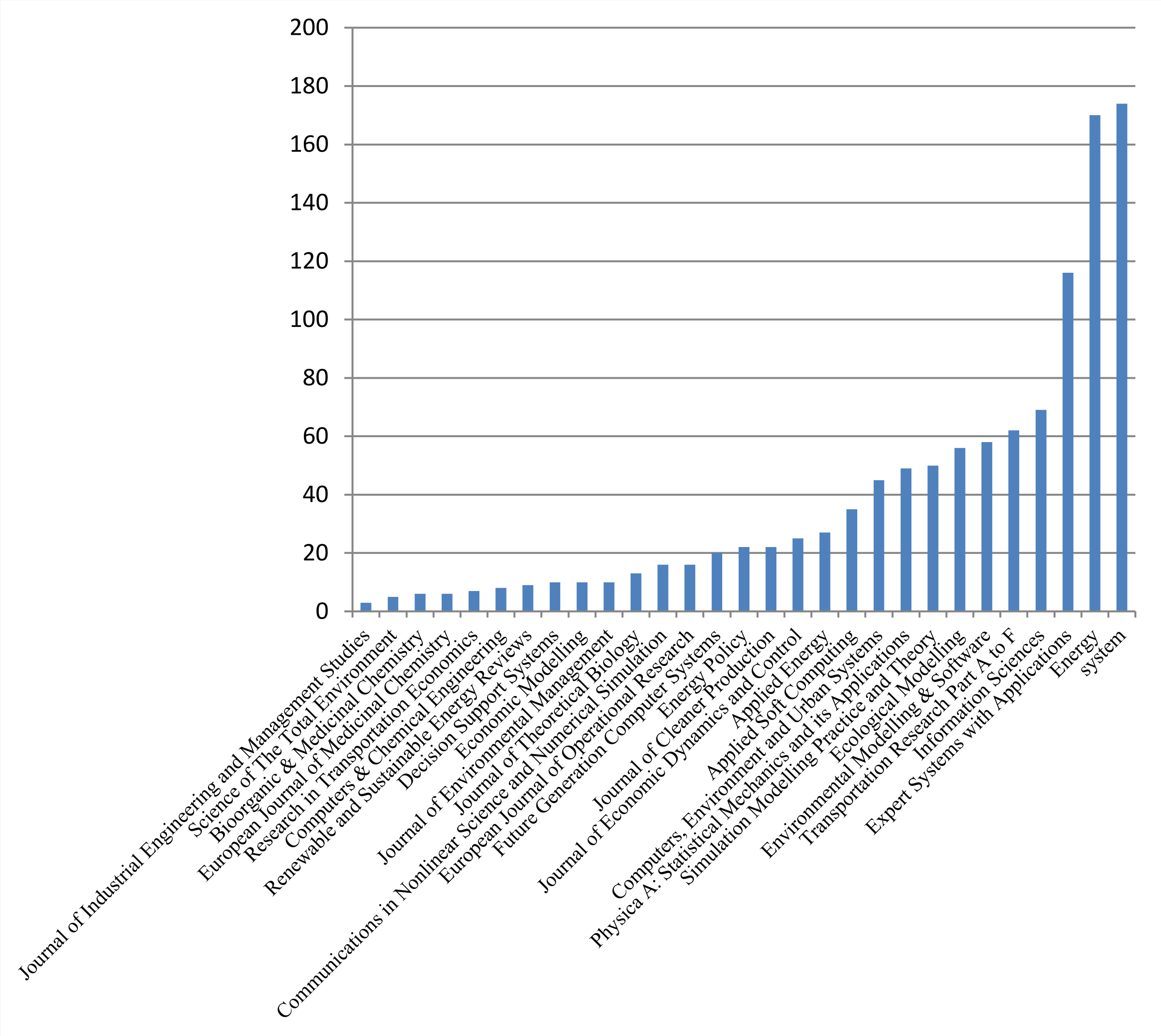

Figure 3. Number of identified articles per journal in year 2010-2019

As presented in Figure 4, from 2010 to 2019, the growing trend of applying the agent-based modeling and simulation approach in research in various fields of science is evident. This means that today, scientists of various sciences have realized the importance of complexity in their field and are trying to understand it and solve problems with different levels of complexity. A review of selected articles indicates that software such as NetLogo, AnyLogic, Jade, Mason, Repast and Swarm, as well as programming languages such as Java and Python, have often been used to conduct this type of researches.

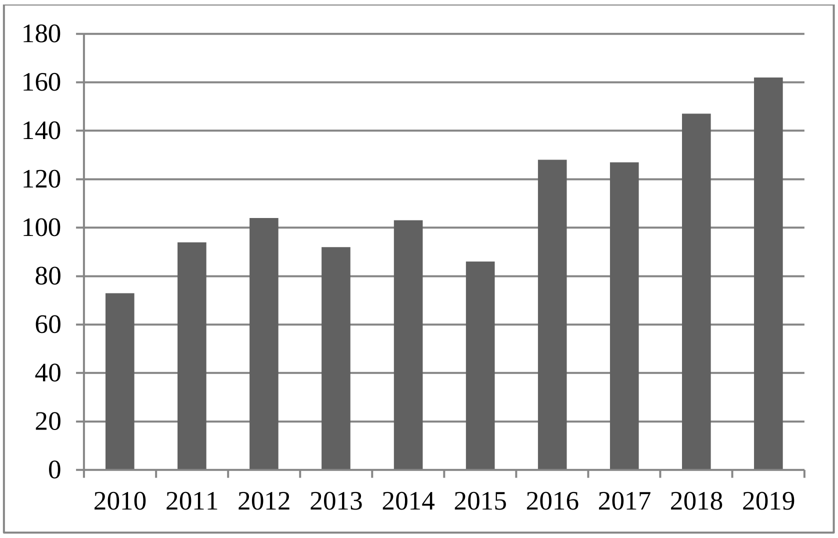

Fig. 4 Number of identified articles per year of publication

3.1 Thematic relevance to applying the ABM in various scientific fields

In the following, 20 categories of 94 selected articles are described. This can remind those interested in complex adaptive systems in various fields that can research with an ABMS approaches to solve their complex problems. At the part of this section, the issue of complexity in the supply chain management is reviewed and discussed.

3.1.1 Experimental sciences and biology

Experimental sciences and biology are disciplines in which ABMS is deeply viewed as a practical tool. Holcombe and Coakley (2006) confirmed the prevalence of application of ABM in complex systems, and at the same time, pointed out the application field properties and sometimes their "ad-hoc". Their research includes the creation of operating systems in virtual environments that could be an applied technology for experimental medicine and biology researchers. Ginovart and Prats (2012) developed an individual-based model that simulates the dynamics of a bacterial bio-reactor under different transmission protocols. As an important decision, choosing a basic modeling method both at the population level and based on the individual must be considered given the problem at hand. Because NetLogo can synchronize all the instructions given to a set of people so that they all work independently with each other and with the environment, they have used this software.
Developing a suitable (flexible, comprehensive, and convenient to use) computational tool which can simulate osmosis through an asymmetric membrane oriented in pressure retarded osmosis (PRO) mode in a wide variety of scenarios, Taherian et al. (2018) proposed an ABM in NetLogo platform, which is an easy-to-use application environment with graphical visualization abilities and well suited for modeling a complex system evolving over time. According to Suarez-Munoz et al. (2019), INSTAR is an ABM to simulate the population dynamics of a kind of forest pest. Using several interconnected modules, INSTAR designed to facilitate the incorporation of new knowledge about the pest biology and serve as template for the design of other similar models. For more broadly enabling observation of molecular transport throughout the different membrane layers and the study of molecular concentration effect in cellular noise, Maia et al. (2019) proposed an ABM to describe single-molecule transport through the cellular envelope of "Escherichia coli" at the micro-meter scale. Proposed model ensured stochasticity in the location of agents, using diffusing spherical

particles with physical dimensions. The summarizing of the experimental sciences and biology domains which employed ABM approach is presented in Table 4.

Table 4. Identified domains of the experimental sciences and biology researches with the AB approach

	Ref.	Domain
Experimental sciences and biology	Holcombe and Coakley (2006)	Medicine and biology
	Ginovart and Prats (2012)	Bacterial bio-reactor
	Taherian et al. (2018)	Osmosis simulation
	Suarez-Munoz et al. (2019)	Population dynamics of a kind of forest pest
	Maia et al. (2019)	Single-molecule transport

3.1.2 Energy

As presented in Table 5, bioenergy, energy consumption behaviors and energy transfer are among the issues that have been considered by researchers in the field of complex adaptive systems as well as ABMS in the field of non-renewable and renewable energy. In recent years, the oil and gas industry has been altering into a more heterogeneous and miscellaneous network of businesses and the oilfields are getting smaller and more diverse. Dwindling the oil reserves and growing specialized companies, which are able to extract hydrocarbons, could be a reason. Restructuring and globalization of the entire business as well as some new technology implementation (Maktoubian et al., 2018) can be stated as other reasons. The complexity of this industry, which stems from its connection to most supply chains, prompted Maktoubian et al. (2018) to pay close attention to optimize the supply chain in the oil and gas industry using ABM integrated to big data technology. Focusing on the Middle East route as the research objective for china's oil imports and by multi-agent modeling and simulation method, Shen et al. (2019) built a multi-agent model for energy transport process in which, oil carrier, pirate and hurricane chose as the agents after security factors evaluation.

Rouleau and Zupko (2019) expounded how ABM can be pertinent to organize a comprehensive bioenergy sustainability assessment to identify possible advantages and trade-offs necessary to evolve bioenergy in regions with large numbers of private family forest owners, or significant share of available biomass which belongs to small holders. Due to the need of renewable energy utilization, especially photovoltaic systems, predicting consumer adaption to different renewable energy models, and determining the resulting impacts on energy system performance in terms of key stakeholders' metrics, Mittal et al. (2019) presented an agent-based model.

Employing historical data to generate distributions for power plant retirements and with the aim of describing the U.S. power plant fleet to compare scenarios for fusion energy technology diffusion, Spangher et al. (2019) suggested an agent based model and simulation, aiming new capacity creation to encounter annual electricity demand. By the exploration of key dynamics of energy transition in the light of the concept of critical transitions, focusing on the role of human behavior and using an ABM tools, Kraan et al. (2019) investigated whether the concept of critical transitions can declare the influence of relevant behavioral dynamics of actors in the energy transition or not.

Ding et al. (2019) developed an ABMS regarding students as heterogeneous individuals and student–student and student–building interactions as a complex system to cope with energy behaviors variability. Jia et al. (2019) exploited a development and validation approach to a novel human behavior model in commercial buildings, using a robust ABM tool, namely Performance Moderator Functions server (PMFserv) as the basis of the occupant behavior considering thermal and visual comforts as well as quality indoor air. In their research, agent-based model represents an office space in building. Sachs et al. (2019) introduced an enhanced building sector model using an AB method to represent the real-world decision making via ability of people to gather information, evaluate the options, and make decisions. Presented model is adaptive to several geographical regions to account for customer needs and cultural differences, and captures several characteristics of consumers' behaviors that influence energy-related investment decisions. In line with evaluating the potential of clean energy promotion to contribute to better policy decisions and measures, Tian and chang (2020) established an agent-based household energy consumption model to capture the habits of different stakeholders and the impact mechanism of critical influential factors.

Table 5. Identified domains of the energy related researches with the AB approach

	Ref.	Domain
Energy	Maktoubian et al. (2018)	Oil and gas industry
	Shen et al. (2019)	Energy transport process
	Rouleau and Zupko (2019)	Bioenergy sustainability assessment
	Mittal et al. (2019)	Photovoltaic systems
	Spangher et al. (2019)	Fusion energy
	Kraan et al. (2019)	Energy transition
	Ding et al. (2019)	Energy behaviors variability
	Jia et al. (2019)	Human behavior model in commercial buildings
	Sachs et al. (2019)	Energy-related investment
	Tian and chang (2020)	Household energy consumption

3.1.3 Environment and greening

Depending on the level of complexity, AMB researchers have been highly enticed the environmental and greening fields. Banitz et al. (2015) paid particular attention to soil organic matter dynamics and its relationship to terrestrial ecosystem functions and Greenhouse Gas (GHG) emissions. Taking into account local interactions and individual variations, they considered individual-based models employing Netlogo to analyze complex microbial systems' behavior based on rules and conditions for individual entities within these systems. They presented a streamlined, user-friendly and open version of the individual-based model INDISIM-SOM, which describes the mineralization of soil carbon and nitrogen. Karslen et al. (2019) developed an agent-based model to explore the effects of policies on CO_2 emissions and imperfect agent information, and split incentives barriers that current shipping models neglect.

To simulate complex socio-environmental couplings in groundwater systems, and exploring how desirable patterns of groundwater and social development can emerge due to agent behaviors and interactions, Castilla-Rho et al. (2015) proposed an interactive modeling environment for developing coupled agent-based groundwater models (GW-ABMs) called "FlowLogo", implementing in the NetLogo platform. Jabri and Zayed (2017) introduced ABM and simulation as an effective bottom-up tool to model earthmoving operations. For earthmoving, they developed an agent-based model, consisting of adaptive and intelligent agents. They assigned a state chart and a set of static and dynamic properties (attributes and variables) to each agent to cope with their interaction with the environment and other factors.

To optimize spatially locate and configuration for greenery, Akopov et al. (2019) developed an agent-based model for air pollution dynamics by the three types of agents, as following: (1) agent-enterprises and agent-vehicles, which are sources of emissions in the city; (2) agent-trees, which consist of small groups of homogeneous closely located trees; and (3) agent-emissions, which are air pollutants produced by agent-enterprises and agent-vehicles. Focusing on the damage patterns within the forest as the final results of multiple tree-wind dynamic interactions during a storm, Kamimura et al. (2019) proposed a simulation model using the ABM technique for forest wind damage. In their research, all agents defined by values denoting either tree resistance against gusts and background-winds (i.e., degree of fatigue of a tree due to pressure from gusts and background-winds) or the natural force of gusts and the background-winds.

Accepting the point that the adoption rate of a new product is affected by the network characteristics of the early adopters, Barbuto et al. (2019) simulated the diffusion process by an agent-based model. Their study aimed to find the network features of the early adopters associated with high adoption rates of using biodegradable mulching films containing soluble bio-based substances derived from municipal solid wastes. Zeng et al. (2020) considered consumers' pro-environmental attitudes and green technology diffusion as an evolving system. So, they proposed an agent-based model that integrates the relative agreement model with technology diffusion theories to organize a sequence of controlled numerical experiments, which steadily reveal how attitudinal and technological factors have effect on green technology diffusion. Table 6 presents the domains of environment and greening issues utilizing ABM approaches.

Table 6. Identified domains of the environmental and greening related researches with the AB approach

	Ref.	**Domain**
Environment and Greening	Banitz et al. (2015)	Ecosystem and GHG emissions
	Castilla-Rho et al. (2015)	Groundwater
	Jabri and Zayed (2017)	Earthmoving
	Karslen et al. (2019)	Effects of policies on CO_2 emissions
	Akopov et al. (2019)	Air pollution
	Kamimura et al. (2019)	Forest wind damage
	Barbuto et al. (2019)	Biodegradable mulching
	Zeng et al. (2020)	Consumers' pro-environmental attitudes and green technology diffusion

3.1.4 Healthcare

As Shetaban et al. (2020) stated, the progress of vaccines, development of hospitals, new medicines, advanced medical equipment, and new treatments preventing death would place the health system indicators at its best state in all ages and centuries. The heterogeneity in the levels of socio-economic development, along with recent disorders in the health system made the field of healthcare attractive to scientists and researchers. Due to various, heterogeneous and interactive actors in the healthcare system, the role of ABM is dramatically appeared. Table 7 shows the 6 main domains of healthcare studies employing AB approach. The global outbreak of coronavirus due to the significant role of human social behaviors as one of the effective agents in the spread and control of this pandemic along with agents such as healthcare system, economy, technology, culture and public policy, could be studied as a Complex adaptive system. The multiplicity of agents and the wide range of their variations, complex interactions between them, along with Coronavirus behavioral changes can be barriers to decision-making for health policy makers. As can be found in Cuevas (2020), Gharakhanlou and Hooshangi (2020) and Silva et al. (2020), the AB approach could be employed to create different scenarios to help decision-makers in the control and treatment of COVID-19 pandemic.

Determining caregivers for patients as well as their routing are among the issues faced by the Home Health Care (HHC) service providers. Centralized offline approaches are commonly used for this type of problem. Marcon et al. (2017) considered a Multi-agent System (MAS) to simulate caregivers' behaviors through four decision-making rules, including: NPR (Nearest Patient Rule), NRR (No-wait Route Rule), SRR (Shortest Route Rule), and BRR (Balanced Route Rule). Liu et al. (2017) developed a systematic method for computerized calibration of a general emergency department model with incomplete data, followed by simulation-based optimization as well as ABM to search for the best value of model parameters. Badham et al. (2018) focused on public health researchers with the potential benefits of an ABM method. They discussed challenges such as appropriately representing behavior mechanisms, obtaining data to calibrate those mechanisms and validate the model, and developing the skills to undertake and report ABM based research. According to Mallory et al. (2019), ABM is useful to simulate a complex system, especially reusing fecal sludge in order to generate value by obtaining public health solutions in growing urban areas in the African desert. Saeedian et al. (2019) developed an ABM considering all different units and actors involving in surgery in the operating room. Considering quality, costs and availability of the local care providers, Chang et al. (2020) proposed an ABM approach to simulate the effects of the Long-term Care Nursing Insurance (LTCNI) on access to care.

Table 7. Identified domains of the healthcare related researches with the AB approach

	Ref.	**Domain**
Healthcare	Marcon et al. (2017)	Home Health Care
	Liu et al. (2017)	Emergency department
	Badham et al. (2018)	Public health
	Mallory et al. (2019)	
	Saeedian et al. (2019)	Surgery
	Chang et al. (2020)	Long-term Care Nursing Insurance
	Cuevas (2020)	COVID-19 pandemic
	Gharakhanlou and Hooshangi (2020)	
	Silva et al. (2020)	

3.1.5 Logistics (transportation, routing and traffic)

The interactive nature of logistics, complexity in distribution and transportation networks, routing and traffic are required to employ agent-based modeling approaches (Table 8). Estimating the travel distance of the order picker in manually operated warehouses is difficult, because the warehouse environment is a stochastic one, affected by a great number of parameters. Therefore, Shqair et al. (2014) simulated the different designs using ABM to estimate the travel distance and assess how the different warehouse parameters (number of aisles, aisle length, number of storage blocks, storage assignment policy, routing policy and order size) and their interactions affect the travel distance. Based on Aragao et al. (2019), the management of transport operations is a heartening area for ABM applications. In their research, the agents in multi-agent approach with a dynamic vehicle routing formulation, allow vehicle to deal with new information perceived during the operation along cargo collecting routes, collaboratively.

Holmgren et al. (2012) provided an agent-based simulator for transportation which is more powerful than traditional approaches, including two connected layers as following: physical activity layer and actor decision-making and interaction layer, as well as production. The operational power of proposed approach is because of explicitly modeling of production and demand of customers, capturing the interactions between the actors of the transport chain, heterogeneity, and decision-making processes, as well as aspects of time. For better understanding and enhancing resilience of the air transport system, Blok et al. (2018) proposed an approach in which anticipatory mechanisms are implemented in an agent-based airport terminal operations model to deal with a disruptive scenario of unplanned and challenging passenger demand at the security checkpoint. To analyze security and efficiency, as vital performance fields of air transport systems and the relationships between them, Janssen et al. (2019) introduced an agent-based methodology to consolidate agent-based security risk assessment approach with agent-based efficiency estimation.

Table 8. Studied works for logistics and their contributions

	Ref.	Domain	Contribution
Logistics	Holmgren et al. (2012)	Transportation	Considering physical activity layer, actor decision-making and interaction layer, and production.
	Shqair et al. (2014)	Travel distance	Warehouse parameters (number of aisles, aisle length, the number of storage blocks, storage assignment policy, routing policy and order size).
	Kim et al. (2017)	Route planning	E-BDI framework.
	Blok et al. (2018)	Airport terminal operations	Dealing with a disruptive scenario of unplanned and challenging passenger demand at the security checkpoint.
	Magarino et al. (2018)	Route planning	The effects of different coordination policies in the electric vehicles route planning for charging on the trips.
	Hywood et al. (2018)	Road network	GPUs performance assessment.
	Santos et al. (2018)	Traffic	Model-Based Development (MBD) for Adaptive Traffic Signal Control (ATSC).
	Yin et al. (2019)	Rail transit	Finding the scope, timing and optimizing the release of passenger flow guidance information.
	Davydenko and Fransen (2019)	Deep sea international ports	Meso-level descriptive approach, considering nautical service chain.
	Olusola et al. (2019)	Transport system of university	Social simulation for effect of interventions on travelers' mode choice.
	Aragao et al. (2019)	Vehicle routing	Multi-agent approach with a dynamic vehicle routing formulation.
	Nnene et al. (2019)	Travel demand	Combination of a genetic algorithm and agent-based travel demand modeling.
	Janssen et al. (2019)	Air transport	Security risk assessment approach with agent-based efficiency estimation
	Fern´andez-Isabel et al. (2019)	Traffic	Smart roads coordination.
	Vizzari et al. (2020)	Pedestrian simulation	Plausible way finding.

Kim et al. (2017) modeled drivers' cognition-based en route planning behaviors in a large-scale road network via the Extended Belief-Desire-Intention (E-BDI) framework. As Kim et al. (2017) stated "E-BDI is a probabilistic behavior modeling framework based on agents own preferences of multiple attributes (e.g., travel time and its variance) and daily driving experiences". They proposed a hierarchical en route planning approach to overcome high computational request issue, which is rooted in the E-BDI framework utilizing for the exhibition of drivers' en route planning behavior in a large-scale road network. Magarino et al. (2018) presented an agent-based simulation framework for simulating the effects of different coordination policies in the electric vehicles route planning for charging vehicles on their trips. To assess the impact of the possible performance of GPUs in the microscopic simulation of a single lane road network, Hywood et al. (2018) employed an ABM.

Santos et al. (2018) proposed Model-Based Development (MBD) for ABMS in the field of Adaptive Traffic Signal Control (ATSC), in which to optimize traffic flow, independent agents were responsible for managing traffic light indicators. They showed that their approach to develop agent-based simulations in the ATSC domain reduces workload. By developing a model-driven architecture to include road traffic theories in simulations, Fern´andez-Isabel et al. (2019) suggested a complete framework to simulate individuals involved in road traffic and smart roads coordination.

Considering a transit network design problem as a complex system, after decomposing the problem into its sub-components (the network design and frequency setting problems), Nnene et al. (2019) proposed a combination of a genetic algorithm and agent-based travel demand modeling. Olusola et al. (2019) examined the factors influencing travel mode choice of a diverse set of travelers to and from university and investigated how a mode shift to alternative travel modes can be aroused within the current transport system environment of the university. By the sound of it, they proposed an agent-based social simulation for effect of interventions on travelers' mode choice. Vizzari et al. (2020) proposed an agent-based model for plausible way finding in pedestrian simulation.
Addressing three aspects namely where, when and what type of the guidance information should be released to the passengers, an agent-based model and simulation was proposed by Yin et al. (2019) to find the scope, timing and optimizing the release of passenger flow guidance information in the rail transit network. As Davydenko and Fransen (2019) considered the nautical service chain at deep sea international ports as a complex system, developed an agent-based model simulation for the port nautical services. The proposed model is a meso-level descriptive approach with the aim of adequate modeling of the basis state of the port and capabilities for assessment of future scenarios. The presented model provides an acceptable foundation for a conceptual representation of nautical service chain.

3.1.6 Resilience

Most recently, a significant amount of research have been dedicated to network flexibility, resilience and disaster management. Resilience, as an emerging field of research is analyzed from different perspectives. According to Table 9, more ABM related articles on the subject of evacuation have been found. Wagner and Agrawal (2014) provided a computer-based simulation and decision support system that employed ABM to simulate population evacuation in the presence of a fire disaster. Due to the proposed approach, multi-disaster scenarios have been tested virtually free of charge. Strategic planning for disaster relief and reducing the average travel time of evacuation and reduction of casualties, as well as improving medical care in natural disasters, is inevitable. Noting that, Ardavan and Alem Tabriz (2016) represented the complex relationship between networking and innovation within the SME context, Sauser et al. (2017) argued that access to government funding is the most common way to strengthen SME resilience in the aftermath of a catastrophe. They presented an ABMS to investigate the resilience of a community consisting of small- and medium-sized enterprises (SME) after a disaster event given two hypothesized characteristics inherent in each business (i.e., Type of customer and resilience) and one hypothesized characteristic of the community sensitivity (i.e., belonging threshold).

Table 9. Identified approaches of the resilience related studies with the AB approach.

Resilience	Evacuation	Wagner and Agrawal (2014)
		Rozo et al. (2019)
		Suk Na and Banerjee (2019)
		Delcea and Cotfas (2019)
		Delcea et al. (2020)
	SME resilience	Sauser et al. (2017)
	Humanitarian issues	Wang and Zhang (2019)
	Tourist recovery	Fan et al. (2019)
	Transportation services	Yang et al. (2019)

Incorporating the heterogeneity of tourists, the interaction between agents and some other systematic characteristics, Fan et al. (2019) presented an agent-based model to simulate the tourist recovery after an earthquake. The outcomes of different recovery and improving strategies for the affected destination was evaluated and different scenarios are created to simulate different strategies for recovery, by changing the values of parameters in the model. Through an ABM, Yang et al. (2019) modeled both the cattle industry and transportation services, as two distinct but interdependent systems. They evaluated the robustness of presented network under disaster conditions. Wang and Zhang (2019) developed a prototype of a spatially explicit agent-based model and applied it for evaluating the deviation of end products between supply and demand for humanitarian relief goods in the areas affected by disaster within a specified time frame.

By developing an agent-based discrete-event simulation (ABDES) modeling framework based on an embedded GIS module, Suk Na and Banerjee (2019) have proposed a simulation model for making supervenient natural disaster evacuation planning and enhancing the evacuation strategy periodically. Delcea and Cotfas (2019) discussed the possibility of using agent-based simulations in NetLogo for a classroom with two exits in order to enhance students' awareness on how to behave during an evacuation process caused by a fire. Representing the heterogeneity in people's behavior, their interactions and environment, Rozo et al. (2019) proposed a combined agent-based discrete choice modeling to design an evacuation plan considering aspects of pedestrian behavior and multiple routing strategies. Using 18 students aged 19 to 21 years, in a classical and collaborative classroom, and measuring some aspects such as speed, dealing with obstacles and ad-hoc guided intervention, Delcea et al. (2020) simulated evacuation process by using ABM.

3.1.7 Production and operations management (POM) and manufacturing planning control (MPC)

MPC and POM are vast fields of issues with wide range of complexity that can provide the basis of ABMS applications. Wang and Lin (2009) linked customer service level performance in contemporary organizations to the effectiveness of their production planning and control system (MPCS). In this regard, since production planning and control system used hierarchical planning, a complication such as inflexibility was inevitable. Researchers in this paper were looking for a solution in obtaining product data from Radio Frequency Identification (RFID) technology. They used multi-agent systems in the development of a production planning and control system based on RFID technology. Zhang et al. (2014) considered timely feedback shop-floor information during manufacturing execution stage leads as a critical requirement in achieving real-time production scheduling. To close the loop of production planning and control, they presented an overall architecture of multi-agent-based real-time production scheduling. For collection and processing of real-time shop-floor data to form "machine agent", they used effectively RFID system. For optimum task assignment to the involved machines at the process planning phase based on the real-time utilization ration of each machine, a "capability evaluation agent" was created. For manufacturing tasks scheduling/re-scheduling strategy and methods according to the real-time feedback, a "real-time scheduling agent" was considered. A "process monitor agent" was intended for tracking the manufacturing execution based on a critical event structure.

Because a large-scale semiconductor production system is a complex system, Lin and Long (2011) provided a multi-agent distributed simulation platform to support highly complex semiconductor manufacturing analysis. To provide a flexible infrastructure and a multi-agent coordination mechanism in a distributed environment, they proposed a multi-agent distributed simulation platform framework to ensure that events are aligned in the correct logical time sequence. In their research, a multi-agent collaborative control model has been applied to describe how agents interact with each other. In order to develop the application of agent-based simulation approach in the original manufacturing industry on a large scale, Adediran et al. (2019) suggested an agent-based Production Disruption Inventory-Replenishment (PDIR) framework, including a novel adaptive heuristic algorithm and inventory replenishment strategy which was proposed to overcome the disruption problems. Ruiz et al. (2014) provided an agent-based simulation environment for intelligent manufacturing systems. They believed that the implementation of simulation, as a basic tool for validating methods and architectures, was inevitable for the manufacturing field before the implementation of the factory floor. In particular, multi-agent modeling had found its place in modeling and implementing production systems, because it had features such as mobility, responsiveness and sociability.

Leung et al. (2010) developed an ant colony optimization (ACO) search algorithm in an agent-based system to integrate process planning and shop-floor scheduling (IPPS) with the goal of achieving optimal solutions through an autocatalytic process. Thus, artificial ants were implemented as software agents, and a simulation has been performed to evaluate the performance of the ants' approach. They showed that the ACO algorithm could effectively solve IPPS problems, and agent-based execution could provide distributive computing of the algorithm. Through (1) yielding a dual-clock failure modeling mechanism to precisely generate the maintenance resource requirements; (2) describing a resources scheduling process based on the contract net protocol; (3) analyzing the dynamic change in the spare parts inventory by considering whether the replaced failure components can be repaired or not, and (4) developing a system cost assessment method to compare different scheduling strategies and to select the one that can minimize the expected total cost, Wang et al. (2019), by examining the multi-echelon inventory system with the operation management of multi-component equipment, suggested an agent-based generic evaluation model for the joint planning of resources.

3.1.8 Maintenance

Liu et al. (2019) studied operational support for aircraft maintenance as a critical issue. They proposed a design of an autonomous system to support automatic decision-making for maintenance planning through an agent-based simulation system as evidence to demonstrate the feasibility of the system's principle and algorithms. Table 10 demonstrates the other identified fields in the ABMS applications along with their Contributions.

	Field	**Contribution**	**Reference**
1	Military science	Development of historical analysis by guerrilla warfare underlying causes modeling.	Duran (2005)
2	Marketing	A method to design and validate viral marketing strategies in Twitter by agent-based Social Simulation and a free and open-source simulator.	Serrano and Iglesias (2016)
3	Cloud computing	Design of Simulation Optimization and exploration Framework in the cloud.	Carillo et al. (2017)
4	Public policy	A full ABM platform named "PolicySpace" that is modular and operational, validated and adjusted to the empirical analysis of public policies	Furtado (2018)
5	Artificial Intelligence	Using hybrid simulation models (agent-based modeling and simulation and system dynamics) to create more accurate and reliable Expert Systems (ES).	Lättilä et al. (2010)
		Meta-model guided sequential sampling technique which combines random forests and uncertainty sampling.	Edali and Yucel (2018)
6	Socio-ecological systems	Formal ontologies to solve the problem of transparency and validation of the model.	Gotts et al. (2018)
		A network-ABM (N-ABM) that combines network and complex systems theory to simulate complex evolving spatial networks. The N-ABM generates dynamic spatial network structures that emerge from interactions between the emerald ash borer and tree agents at the individual scale.	Anderson and Dragićević (2018)
7	Human Resource	To integrate behaviorism in modeling the human resource structure evolution.	Rashid et al. (2018)
		The concept of time allowances from two perspectives: industrial engineering and the prevention of occupational risk.	El Mouayni et al. (2019)

8	Finance	Simulated moments based method for a financial agent-based model using realistic order matching procedures.	Platt and Gebbie (2018)
9	Internet of Things	Suitability assessment of the ABC paradigm for the (current and future) IoT development.	Savaglio et al. (2020)
10	Risk	A model for robust information diffusion to identify malicious peers that poses risk in P2P networks to track social interactions between peers to identify and collect a proposed stream.	Jung (2009)
		An ABM and simulation that can be appropriate for design of beneficial tools that facilitate the evaluation of owners' response to policy interventions aimed at reducing the seismic vulnerability of communities by promoting seismic retrofits.	Kashani et al. (2019)
11	Economy	The wealth distribution simulation in the three upper, middle, and lower classes through a computational model of the underlying factor.	Damaceanu (2008)
		An ABMS to analyze and evaluate the behaviors of governance in the Brazilian financial sector under different macroeconomic variables and the different attitudes, perceptions and tendencies of economic and political actors.	Streit and Bronstein (2009)
12	Revenue management	Modeling of seller pricing decisions when the price, as a tool of revenue management, decreases and analyzing revenue changes which influence seller's decision about proper discount rates of products.	Hajy Alikhani et al. (2019)
13	Water	A framework based on ABM to simulate the behavioral characteristics of residential water consumers and their social interactions, as a decision-making tool that can be applied to assess the responses of home water consumers to some factors such as social awareness about hydrological conditions, water pricing, and advertising policies, as well as social interactions and communications.	Darbandsari et al. (2017)
		The ABM applying to address the two-way feedbacks of social-hydrological systems.	Pouladi et al. (2019)
		The agent-based model, urban water stakeholders and determines compatible integrated urban water management strategies included (A coupled agent-based risk-based optimization model with considerations of simultaneous changes of water supply and water demand. The risk-based optimization model intends water scarcity to determine the uncertainty, which reduce by optimal allocation of water resource.).	Bakhtiari et al. (2019)
14	Food	A multi-agent System framework and defining procurement, allocation, milling and scheduling agents with focusing on reducing food wastage during procurement, collection and storage.	Reddy et al. (2016)
		A potential strategies exploration to optimize food consumption in all-you-can-eat food-service operations including maintaining low wait-time, unsatisfied-hunger, and walk-out percentages, in terms of minimizing food waste while ensuring quality of service.	Ravandi and Jovanovic (2019)
		Considering food security decision-making sustainability and by developing an agent-based model in Python environment, a dynamic decision-making scheme that simulates strategies of the perishable food market under different circumstances.	Namany et al. (2020)
15	Social	Dynamic models of individuals using low-level language to simulate the propagation of information among a group of individuals and its influence on their behavior.	Huanhuan et al. (2013)
16	Housing Market Dynamics	Forecasting and analyzing the dynamics of housing market in Lugano by modeling behavior of individuals who are living in this city and a model for the interdependency of these behaviors and the information that flows in the system.	Esmaeili et al. (2010)

3.2 Supply chain network complexity

As stated by Dan Gilmore (2008), "Complexity is simply destroying the profitability at many companies, and that executives often can't see what the true cause is. They blame poor execution of what, in truth, are strategies doomed by the complexity they add, especially in the supply chain. More suppliers, more parts, more forecasting, more customers to ship to and more returns to manage, etc. Our accounting systems also lack the ability to well capture the true cost of this complexity, keeping it hidden." He also quoted Tom Blackstock, Vice President Supply Chain Operations Coca-Cola North America: "If you are in Supply Chain

Management today, then complexity is a cancer you have to fight." Drawing on findings by Perera et al. (2017) and Modrak and Bednar (2016), the reasons for the complexity of supply chain network as a system, due to some differences in the following:

- Topological structures;
- Products, entities, resources, processes and characteristics;
- Members and roles;
- Financial, information and materials flows;
- Interactions and inter-dependencies.

On the other hand, many aspects, including the complexity, openness, emergence, and dynamics of the structure reflect the complexity of supply chain network (Wang et al., 2018). Based on findings of Serdarasan (2013), drivers of supply chain complexity are listed in Table 11.

Table 11. Identified drivers of supply chain complexity.

According to type		According to origin		
		Internal	**Supply/demand interface**	**External**
1	Static	Number/variety of products Number/variety of processes	Type of product Number/variety of suppliers Number/variety of customers Process interactions Conflicting policies	Changing needs of customers Changing resource requirements New technologies
2	Dynamic	Lack of control over processes Process uncertainties Employee related uncertainties Unhealthy forecasts/plans	Lack of process synchronization Demand amplification Parallel interactions	Changes in the geopolitical environment Shorter product lifecycles Trends in the market Market uncertainties Developments in the future
3	Decision-making	Organizational structure Decision making process IT systems	Differing/conflicting decisions and actions Non-synchronized decision making, Information gaps Incompatible IT systems	Changes in the environment Factors that are out of span of control Uncertainty of the unknown/uncontrollable factors

Due to complexity and difficulty of forecasting, it would be hard to control and manage supply chain networks (Surana et al., 2005). The collective system behavior emerges as a nonlinear and dynamic function of the large number of activities, made in parallel by interacting entities (Pathak et al., 2007).
Supply chain networks must be considered not only a system, but also as a complex adaptive system to overcome the lack of understanding of the organizational, functional, and evolutionary aspects of supply chains (Surana et al., 2005). Choi et al. (2001) argued that supply chain networks in large scale are complex adaptive systems, where an interconnected network of multiple entities exhibit adaptability in response to changes in both the environment and the system itself. In this regard, the assumption "a CAS supply chain will contain numerous components with functions and inter-relationships that imbue the system as a whole with a particular identity and a degree of connectivity or connectedness", proposed by Choi et al. (2001).
ABM is dominant tool exploring the emergent behavior of supply chain network with a large number of interactive agents. The next section is devoted to the studies related to ABM employing in supply chain problems. Knowing when to use agent-based modeling and simulation, the current application of this method, some examples, general definitions, and the structure of this method, review of Macal and North (2005a, 2006b, 2007c, 2010d, 2011e, 2013f; 2014g) and Macal (2018) is highly recommended.

3.2.1 Thematic relevance to ABM approach for complex supply chain problems

Zhang et al. (2006) considered how to provide efficient and cost-effective responses to unpredictable changes in a global marketplace as one of the main problems of organizations. They proposed an approach to integrate supply chain based on the concept of dynamically integrated manufacturing systems (DIMS). DIMS refer to manufacturing systems, within an enterprise or across a supply chain, that are dynamically integrated for optimal performance in response to changes in the market/business environment. Based on findings of Zhang et al. (2006), dealing with dynamic changes in the supply chain achieves by synergizing two emerging concepts: agent-based agile production systems and electronic manufacturing.

Allen et al. (2006) presented an agent-based computational framework for studying a multi-product complex multi-country supply chain subject to demand variability, production and distribution capacity constraints with the aim of improving operational resilience in terms of several supply chain performance measures. They judged the operational resilience in terms of customer service level, change over, average inventory and total average network inventory as the performance measures for each agent. In order to make the agents true representation of real business units, they divided the agents (factory and distribution center) structure into two stages: the functional and the decision-making stage. They proved that the use of complexity science, in addition to strategic exploration of structural change and major innovations, could be employed to improve the operational resilience of real systems.

Labarthe et al. (2007) proposed an agent-based framework as a more elaborate tool compared to traditional forecasting models, for the modeling and simulation of supply chains, to facilitate their management. Their proposed methodological framework was structured according to three levels of conceptual, operational and experimental preoccupation. For each level they defined specific models as well as their elaboration processes. Chatfield et al. (2007) discussed that many supply chains are order-oriented; on the other hand, the ABM cannot effectively deliver the order life cycle. So they offered a conceptual architecture that allowed for a natural and realistic display of the various supply chain structures and subsystems, while at the same time following a general overview, during which an agent represents a supply chain infrastructure while enabling a process-oriented approach to epitomize orders. Their proposed architecture included a consistent viewpoint for representing supply chains, carried forward from start to finish and providing a level of modeling consistency lacking in many other approaches to supply chain simulation.

Li et al. (2009) introduced the supply chain as a complex adaptive system, in which the structure and mechanism of cooperation develop over time. In their study, based on the theory of complex adaptive systems and fitness landscape, they proposed an evolution model of Supply Network (SN) based on CAS and fitness landscape theory to gain understanding of the evolution of the SNs. As Li et al. (2009) stated, an SN emerges from the dynamic interactions among the firms and evolves over time, and the evolution is self-reinforcing and path-dependent. Based on their findings, slight perturbation of the environment and the internal mechanism of firms could lead to chaos in the evolution as well as difficulty in predicting.

Tounsi et al. (2009) proposed an agent-based meta-model for small and medium enterprises supply chain. The main objective of their study was to capitalize the "know-how" techniques in order to simplify supply chain modeling and concepts reuse to study the dynamic behavior of the agent-based meta-model and to implement a simulation platform for supply chain that mostly involved small and medium enterprises. Um et al. (2010) believed that supply chain management was a management model and an important strategic factor for competition in environments that are suddenly changing. They stated that, negotiating among all members was inevitable in order to maximize profits across the supply chain. Therefore, in order to find the best negotiation strategy, and subsequently to maintain the satisfaction of all members of the supply chain, Um et al. (2010) chosen a multi-agent approach, with factors such as price, checkpoint and delivery time, to solve the problem. In this way, an agent automatically performed certain tasks using cooperation or negotiation with other representatives on behalf of a human being based on real-time communication.

Emphasizing the importance and benefits of operational supply chains as an integral part of modern manufacturing companies as well as the importance of data sharing as the main need for effective supply chain performance, Uppin (2010) proposed a multi-agent model for supply chain design that led to the efficient sharing of information and the integrated performance of the various units of an organization, and the strengthening of communication with other joint ventures. Li et al. (2010) examined the behavior of dominant players in supply chains using a multi-agent simulation model to analyze behavior based on experiments results. Based on their research, the main sources of uncertainty for the behavior of dominant players included market information, selling price, and purchase price. Employing Stable Profit Platform (SPP) to indicate the level of domination power for the player achievement, the relationship between the rational purchasing and selling prices of the period of SPP was shown by their model. According to their findings, since the domination power determined the position (follower or leader) of players in the game, the dynamic level of domination power would influence the negotiation among the players.

Giannakis and Louis (2011) developed a framework for the design of a multi-agent-based decision support system for the management disruptions and mitigation of risks in manufacturing supply chains. Their proposed framework focused on demand driven supply chains rather than supply chains driven by forecasts, since for the latter risk could be mitigated through stock piling of inventories, in order to achieve high throughput but low volume. Holmgren et al. (2012) provided an agent-based simulator for transportation, including two connected layers: physical activity layer and actor decision-making and interaction layer, as well as production, which was more powerful than traditional approaches. The more operational power of this approach was due to the fact that it explicitly modeled the production and demand of the customer and captured the interaction between the actors of the transport chain, heterogeneity and decision-making processes, as well as aspects of time. They showed that it was possible to deal with the complexities of mixing timetabled and demand driven transports in the algorithmic approach and simulate the principles of EOQ by letting the customer select the best order quantity among a set of possible quantities. Holmgren et al. (2012) concluded that, the interaction framework was appropriate for capturing the ordering process in a multi-agent-based transport chain simulation model for analysis.

For calculating the risk levels of palm oil supply chain, Hedayat and Ridvan (2013) applied fuzzy analytical hierarchical process method to identify risk factors for the high level of supply chain, and the ABM to balance level of benefits to weight the risks to the perpetrators or stakeholders. Due to the complex nature and numerous interacting factors that contribute to the increased vulnerability of supply chains, Chen et al. (2013) used a multi-fact viewpoint to present various agent-based modeling and simulation researches in the field of supply chain risk management, focusing namely on supply chain risk management processes, planning decision levels, and supply chain design goals. Hidayat and Marimin (2014), focusing on the Palm oil supply chain, designed an agent-based model to simulate interaction and negotiation of actors and facilitate optimal value-added distribution, while considering successive investments and operational risk levels. They showed that all actors in the Palm oil supply chain needed to consider overall supply chain sustainability while conducting pairwise negotiation. Ponnambalam et al. (2014) believed that multi-agent approach at modeling supply chain network as the complex adaptive systems, and investigating the supply chain network's structural characteristics via social network analysis could be profitable. Their approach provided a better chance to achieve better understanding the emergence of complex supply chain networks, assessing the network vulnerability after its emergence and studying the robustness, resilience of the network to hypothetical internal/external disruptive scenarios.

In terms of coordination in supply chains, Christos et al. (2016) developed two agent-based models using two distinct software platforms with considering as follows: a) "taking into account the dynamic nature of supply chains, central coordination techniques are considered of high risk, as they are not resistant to changes and have a single point of failure", and b) decentralized management as a prerequisite for being networks flexible and effective, because of nodes necessity to dynamically move in and out of the supply chain and ability to support decision-making. Supporting the analysis of collaborative relationships in supply chain interactions, Dorigatti et al. (2016) presented an extension to the service-oriented framework for performing ABS's. In this extension, a new service for simulating the planning of transportation was designed to allocate finite transportation resources to the transportation orders, and the service consists of the functionality that tied the needed vehicle type, location and time to find the availability of a vehicle fleet as it was allocated to a plan.

Due to the importance of agri-food supply chains in operations management science and increasing the use ABMS in this field, Utomo et al. (2017) reviewed the application of this approach in the field of agri-food supply chain. Their findings were as followimng: Cooperation and competition, buyer-seller relationships and services are under consideration. Leading actors in the agri-food supply chain, such as food processors, supermarkets and retailers, received less attention with ABMS approach. Ghadimi et al. (2018) considered the process of evaluating and selecting a sustainable supplier in the industry 4.0 supply chains, in which connection, real-time information transparency, technical assistance and decentralization of supply chain members were mentioned as design principles. They offered a multi-agent systems (MAS) approach to addressing the process of evaluating and sustainably selecting a supplier to provide an appropriate communication channel, structured information exchange, and visibility among producers and manufacturers.

Finding trust as a fundamental predictor of positive performance outcomes and competitive advantage in supply chain, Hou et al. (2018) examined the relationship between trust as a fundamental predictor of positive performance outcomes, and competitive advantage in supply chain and interdependence structure of supply chain. Based on complex adaptive theory, they built a multi-stage multi-agent supply chain framework to explore whether and how the trust affected the interdependence structure in the supply chain and therefore affected the supply chain network's resilience against both random and targeted disruption. Their study showed that although the trust-based supply chain network was not a scale-free-like pattern, it had some excellent system resilience against the propagation of both random and targeted disruptions. Behdani et al. (2018) presented an agent-based simulation framework that supported decisions in different steps of pre/post-disruption processes for supply chain disruption management. They modeled two strategies to handle supplier disruptions as following: inventory mitigation and sourcing mitigation. They addressed flexibility as an important feature of thier proposed modeling framework to model different types of disruptions in both social and technical entities in the supply chain.

Tayyaran et al. (2019) by using ABM in Netlogo environment and impressive elements such smooth, offender and fault case, which those are also categorized in two groups impressive and impressible, attempted to simulate the agility of supply chain in an institute of higher education. Considering to their analysis and evaluation, it could be observed that even if model avoided the elements which led improvement to ruin, there was no guarantee to increase agile amount and only impressive elements could control organization from created risks by offender elements. By developing an agent-based system, Heidary and Aghaie (2019) addressed a new multi-period and scenario-based supply chain model consisted of a number of unreliable suppliers and two types of retailers facing risk sensitive and risk neutral in the form of a multi-period newsvendor problem with a risk averse objective function. They proposed an approach to calculate the risk averse profit functions by employing the Monte Carlo simulation and developed agent based simulation model, comparing the efficiencies of a genetic algorithm and a Q-learning.

By focusing on the Kanban and Drum-Buffer-Rope (DBR) scheduling mechanisms, Puche et al. (2019) considered lean management and theory of constraints, and evaluated their performance in a four-echelon supply chain operating within a large noise scenario. With this in mind, they proposed an agent-based system as a powerful model-driven decision support system for managers. The financial performance of supply chain based on lean management and theory of constraints were compared, examining the impact of the noise. Considering supply chain networks as complex adaptive systems and by modeling how disruptions propagate in the supply chain network through cascading failures, Zhao et al. (2019) proposed, evaluated, and analyzed two types of adaptive strategies to enhance supply chain network resilience by developing an ABMS. They modeled and analyzed the impact of disruptions on a real-world large scale supply network and demonstrated the use and effectiveness of reactive strategies, developed and evaluated the effectiveness of proactive strategies for firms to improve their resilience against a distant disruption, and analyzed factors related to the performance of proactive strategies. Table 11 summarizes the main findings of supply chain articles related to the topic in terms of domain and agent or type of the articles approach.

Table 12. Summarizing SCM related researches with AB approach

	Domain	Ref.	Country	Agent models/Specification
1	E-manufacturing and and SC integration	Zhang et al. (2006)	China	Job, resource, leader, supply network, product, inventory mgt., product data mgt., and order handling.
2	Operational Resilience	Allen et al. (2006)	UK	Factory and distribution center.
3	Customer-centric SC	Labarthe et al. (2007)	France	A methodological framework for agent-based modelling and simulation of SC.
4	Order-centric SC	Chatfield et al. (2007)	USA	Conceptual architecture
5	Supply network evolution	Li et al. (2009)	China	Firms
6	SMEs mechatronic SCs	Tounsi et al. (2009)	France	Conceptual meta-model
7	Negotiation algorithm in the SCM environment	Um et al. (2010)	USA	Trading, buyer, seller, communication
8	Operating SCs	Uppin (2010)	India	Stock, MPS, RCCP, Product Data, BoM, Time Phasing, Vendors Data, Vendor Rating,
9	Dominant player's behavior of SCs	Li et al. (2010)	China	Raw supplier, Component supplier, Manufacturer, Retailer
10	SC risk	Giannakis and Louis (2011)	UK	Communication, coordination, monitoring, wrapper, disruption manager
11	Transport chain	Holmgren et al. (2012)	Sweden	Customer, production & transport planner, transport chain coordinator, transport & product buyer
12	Upstream palm oil SC	Hedayat and Ridvan (2013)	Indonesia	Farmer, collector, CPO mills
13	SC risk	Chen et al. (2013)	Singapore	Survey
14	Real-time production scheduling	Zhang et al. (2014)	China	Machine, Capability Evaluation, Real-time Scheduling and Process Monitor Agents
15	Operational Risk	Hedayat and Marimin (2014)	Indonesia	Palm oil SC actors
16	Robustness and resilience of SC	Ponnambalam et al. (2014)	Singapore	Seller and buyer
17	SC modeling	Christos et al. (2016)	Greece	Comparative Study
18	Transportation	Dorigatti et al. (2016)	Argentina	SC members
19	Agri-food supply chains	Utomo et al. (2017)	UK	Bibliographic mapping
20	Sustainable supplier selection	Ghadimi et al. (2018)	Ireland	Supplier, Data Base and Decision Maker
21	Resilience of SC topology	Hou et al. (2018)	China	Firms
22	Disruption management in chemical SCs	Behdani et al. (2018)	Netherlands	Disrupted object
23	SC agility	Tayyaran et al. (2019)	Iran	Smooth, offender and fault
24	Risk in stochastic SC	Heidary and Aghaie (2019)	Iran	supplier, retailor, customer and spot market
25	Kanban and Drum-Buffer-Rope	Puche et al. (2019)	Spain	Node, event and entity
26	SC resilience	Zhao et al. (2019)	Hong Kong	Firm/node

4. Conclusion and directions for future research

For a variety of reasons, including the interactive nature of entities (interactions between entities as well as between entities and their environment), the rules governing systems as well as agents, interrelationships and self-organization, a supply chain networks with the high level of complexity cannot be studied in detail. Complex supply chain network should be considered as a complex system (as a whole) which has the characteristic of being adaptive. In such complex adaptive systems, minor changes in input can significantly affect the entire system. Such problem cannot be considered solved permanently, and with every small change in the behavior of agents and entities, a new problem emerges as a different problem with different solution. Agent-based modeling is potentially applicable for such systems. ABM examines how agents interact with each other and their environment to achieve a goal and analyzes the emerging behaviors of systems and their parts (Huanhuan et al., 2013). Focusing on research questions, we have conducted a systematic literature review. The findings show that, fields such as experimental sciences and biology, energy, environment and greening, healthcare, logistics (transportation, routing and traffic), resilience, MPC & POM, maintenance, military science, marketing, cloud computing, public policy, artificial intelligence, socio-ecological system, human resource, finance, internet of things, risk, economy, water, food and housing market dynamics have been employed ABM approach.

On the other hand, after reviewing the identified articles, the domains related to supply chain networks studies in association with ABM approach identified as following: agile production systems, electronic manufacturing, order life cycle, SME’s SC, negotiation strategies in SC, efficient sharing of information, integrated performances, behaviors examination of market information, selling price and purchase price, supply chain risk management, SCOR model, palm oil supply chain, supply chain resilience, agri-food supply chain, supply chain sustainability and Kanban and drum-buffer-drop scheduling for multi-echelon SC. One of the main objectives of this research is to provide a perspective, based on agent-based modeling and complex adaptive systems for researchers in different sciences and especially SCM researchers, who are not sufficiently familiar with the philosophy and applications of these approaches. Lack of access to an accurate and complete framework, structure and standard for designing agent-based model was a limitation of this research. So this is one of the issues that could be suggested as a future research. Some areas proposed by our work can be extended as a new SLR for each domain. However, several directions are suggested for future research. Firstly, the review on supply network AB models identified a gap in the study of the pharmaceutical distribution networks resilience during COVID-19 pandemic.

For further research, a comprehensive review of the hybrid application of metaheuristic algorithms and agent based modeling is highly recommended. Employing ABMS to analyze opportunities of the post-Coronavirus era can be studied for supply chain networks considering financial and commercial indicators to produce different decision-making scenarios. exploiting broader databases with a focus on reviewing creating AB model frameworks for specific types of supply chains and their evaluation indicators is recommended as future research.

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