# Simulating Systems-of-Systems with Agent-Based Modeling: A Systematic Literature Review

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***Abstract*—In this work, we conduct a systematic review to investigate how agent-based modeling (ABM) techniques have been applied for simulating Systems-of-Systems (SoS) domains. We understand that modeling and simulating SoS is a hard task and must be conducted by techniques (e.g. ABM) that represent the behavior of agents and the operation of a SoS to overpass this complexity. We evaluate the most utilized models, approaches, and tools. We also investigate how accurate are the SoS simulations performed by this technique and which are the most investigated problems. As a result, we identify which tools and approaches have been utilized to investigate the behavior of SoS.**

***Index Terms*—Systems-of-systems, Modeling and simulation, Systems agent-based modeling, Systems-of-systems engineering, Systems Model-driven development.**

## I. Introduction

Systems-of-Systems (SoS or SoSs) correspond to a set of heterogeneous systems able to generate emergent behaviors based on their interactions [3]. This kind of system is designed for producing novel capabilities that would not occur if these systems did not unite to achieve a common goal. Each constituent system has operational independence and can also have managerial independence [29]. In this case, a SoS can be designed by considering the following types [9]: (i) directed SoS, which contains a coordinator agent that controls (with authority) all the constituent systems of this SoS; (ii) acknowledged SoS, which also contains a coordinator agent but it only manages its constituent systems without claiming some kind of commitment; (iii) collaborative SoS, which contains a decentralized control (i.e. there is no coordinator agent) to establish collaboration among its constituent systems; and (iv) virtual, which also does not have a central controller and is designed for depending on invisible mechanisms to perform its overall purposes.

There are three techniques able to simulate the dynamics of a SoS (i.e. its types, behaviors and capabilities) [21]: (i) systems dynamics; (ii) discrete event-based model; and (iii) agent-based model (ABM). Among these techniques, ABM is a bottom-up technique that utilizes agents to represent the modeled domain [32]. An agent is a piece of software with autonomy and rules that addresses decisions by incorporating information of a given environment. They learn about this environment and evolve over time. ABM is employed by the following reasons [17]: (i) ABM knows to deal with all the complexity of interactions between constituent systems; (ii) ABM provides the necessary dynamics for investigating emergent behaviors; (iii) ABM follows the same principle of a SoS (i.e. guided by objectives, autonomicity, and adaptability); (iv) ABM is a powerful technique able to model and to simulate various heterogeneous constituent systems; and (v) ABM represents a large variety of different systems even when just a few rules are introduced.

In this work, we elaborate a systematic literature review to know whether ABM is suitable to simulate SoS. We investigate the application of agent-based models by identifying how these models can be employed to better develop a SoS. We identify which are the most utilized application domains as well as which methods, approaches, and tools have been extensively utilized to simulate these kinds of systems. The work structure is presented as follows. In Section II, we present the chosen method to perform all the systematic review. In Section III, we highlight the main results found in this review. In Section IV, we discuss some aspects related to the findings of our SLR. In Section V, we present the concluding remarks of this article.

## II. Method

A Systematic Literature Review (SLR) is a method that identifies, selects, evaluates, and synthesizes evidences about research questions, area of interests, or a given phenomenon. According to Kitchenham and Charters [22], this method is composed by a protocol divided into three stages: (i) planning; (ii) selection; and (iii) report. We utilize software tools that support all the stages of this review. The StArt (State of the Art through Systematic Reviews) [12] tool is employed at the stage (i) and at the stage (iii), the Mendeley Desktop tool [39] is employed at the stage (ii), and the LibreOffice Calc tool is utilized to organize and to summarize the research findings.

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### A. Stage 1: SLR Planning

This stage defines the research protocol that will be utilized in the review. We have adopted the protocol from the StArt tool as a reference, which is composed by the following elements [12]: (i) definition of the research questions; (ii) identification of keywords; (iii) identification of sources and their criteria; (iv) elaboration of inclusion and exclusion criteria; and (v) search strategy. Each element is essential for accurately identifying the most recent researches in SoS that apply agent-based models to simulate different domains.

*1) Research*

: A SLR must address questions that will guide the research. These questions must be raised to better understand how agent-based models can be utilized to simulate SoS in domains like government, industry, military, and academical. Also, keywords and synonyms must be identified to support the construction process of the search string. We consider the wave model as one of the most utilized models to represent the SoS engineering process over time [8]. We assume that modeling and simulation are essential stages to conduct SoS analysis, one of the driving characteristics of this model. Therefore, we perform a systematic review to answer how agent-based models must be applied to simulate SoS engineering related-aspects. This is better evaluated by dividing this main question into other four sub-questions, as depicted in Table I.

TABLE I: Research questions considered in this SLR

| **Primary Question** |
|---|
| RQ: How does Agent-based modeling (ABM) support SoS engineering (SoSe)? |
| **Secondary Questions** |
| RQ1. Which models have been applied to perform SoS agent-based simulations?<br>RQ2. Which approaches are essential to provide SoS agent-based simulations?<br>RQ3. Which tools the researchers have utilized to perform SoS agent-based simulations?<br>RQ4. Which domains have been investigated to perform SoS agent-based simulations? |

*2) Research Sources*

: Developing SoS simulations by utilizing agent-based models require background in various areas of knowledge. Therefore, it is essential to choose research sources that encompass this multidisciplinary field. In this work, we have chosen the following sources related to computer science and engineering: (i) ACM; (ii) Engineering Village; (iii) IEEE; (iv) ISI Web Of Science; (v) ScienceDirect; (vi) Scopus; and (vii) Springer.

*3) Strategy*

: To perform this research, we utilize only electronic databases with web search engines. To identify the target studies of this SLR, we consider the following search terms:

(1) (“System of Systems”) OR (“Systems of Systems”)
(2) (“System-of-Systems”) OR (“Systems-of-Systems”)
(3) (“Agent-based modeling” OR “Agent-based model”)
(4) “Model” OR “Approach”
(5) “Technique” OR “Method”
(6) “Framework” OR “Simulator”

We combine these terms in the following way: *(1 OR 2) AND 3 AND ( 4 OR 5 OR 6)*. We utilize the search engines of the chosen scientific associations as a search strategy to perform the collecting of these articles by using the search in the advanced mode to filter the type of published work. We define these terms by considering the SLRs published in [23] and [28], which highlight the usage of the same synonyms of SoS utilized in this work. We apply the same search terms into all the research sources. We utilize parenthesis to link each keyword with its adjacent and apostrophes to enclose the expression as a unique word. Likewise, we gather a high amount of studies strongly related to our research questions.

TABLE II: Quality criteria to assess the selected studies in this SLR

| # | Questions |
|---|---|
| 1 | Is the paper structure well defined (organization and writing)? |
| 2 | Is the literature well presented and relevant? |
| 3 | Is the research problem well stated (contextualization and related work)? |
| 4 | Are the research questions well formulated? |
| 5 | Is the proposal well presented and feasible (realistic)? |
| 6 | Is the experiment reproducible and well defined? |
| 7 | Is the statistical analysis presented? |
| 8 | Does the paper develop a well-formulated discussion? |
| 9 | Is the research applicable into other contexts? |
| 10 | Is the further research well defined? |

*4) Criteria*

: To evaluate the quality of the studies, we define three types of criteria to select those studies with high level of quality: (i) inclusion criteria; (ii) exclusion criteria; and (iii) quality criteria.

In the inclusion criteria table, we identify studies that match with our research questions and that decrease research bias. We consider only full primary papers that are written in English. These papers must also address the usage of agent-based models for simulating SoS related-aspects.

In the exclusion criteria, we eliminate those studies that do not contribute with the inclusion criteria such as secondary papers, non-English written papers, redundant, duplicated or unavailable papers. Furthermore, we eliminate those papers that only address topics related to ABM or SoS or studies that do not encompass the usage of ABM to simulate SoS. We also define as an exclusion criterion that each study must reach a minimum quality threshold to be accepted in this SLR.

In the quality criteria, the selected studies are scored through a set of 10 criteria defined in Table II to evaluate writing and structure of these studies. Each criterion is a question that must be answered according to the assessment of the authors of this work. For each question, we score with the value 1 in case the answer is positive, with the value 0 in case the answer is negative, and with the value 0.5 in case the answer is undefined (we define ’ML’ as an abbreviation of ’More or Less’). For each evaluated study, we sum the scores obtained from these answers to define a final quality score.

To properly investigate the results obtained in this review, we also define which data must be considered by a selected study during the extraction process. Table III presents the list of categories and fields that must represent information about the studies.

TABLE III: Extraction Form Fields

| # | Data Categories | Fields |
|---|---|---|
| 1 | Publisher | (IEEE, Elsevier, ACM, Springer, ASCE, Wiley) |
| 2 | Publication Year | (extracted from metadata) |
| 3 | Application Context | (Academy, Industry, Government, Military) |
| 4 | Key Contributions | (Approach, Model, Framework, Simulator) |
| 5 | Type of SoS | (Directed, Acknowledged, Collaborative, All types, Not specified) |
| 6 | Research Method | (Use Case, Case Study, Illustrative Scenario, Prototype, Not applicable) |

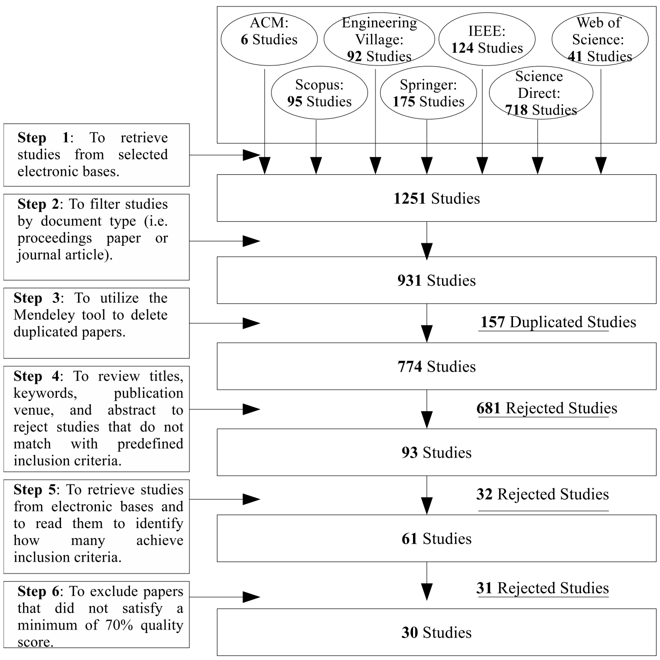


Fig. 1: Paper selection flowchart

## B. Stage 2: SLR Execution

This stage is responsible for running the protocol elaborated in stage 1 through a set of steps that filter the most relevant works to answer the research questions. Fig. 1 depicts the set of 6 steps to choose relevant studies about ABM in SoS and how many papers were selected in each step. We ran the SLR protocol on February 22, 2019, by collecting, analyzing, summarizing, and organizing the studies of the chosen scientific sources.

The step 1 retrieves studies from sources by utilizing the search string defined in this protocol. The step 2 utilizes a filter available in each source to select only studies published in proceedings or in journals. This filter excludes studies that are encyclopedias, standards, courses, reviews, books, among others. The step 3 excludes all the duplicated papers or those works with high level of similarity, and the Mendeley tool is used to perform this task. The step 4 is responsible for reviewing titles, keywords, publication venue, and abstract to exclude those papers that do match with the inclusion criteria but do not match with the exclusion criteria. The step 5 retrieves the included studies in step 4 and downloads the respective papers for reading. The step 6 is responsible for defining a quality score for each selected paper. Table IV lists the selected studies, with an ID for future reference along the text, the study title and reference.

## C. Stage 3: Report

After performing search and selection of candidate studies, we extracted data of the 30 included studies in this SLR to obtain a more accurate information about these studies and their contributions. We have collected information about the types of SoS investigated, which resources were employed, in which application domains ABM is utilized with SoS, which were the main investigated problems, and in which application context ABM and SoS were utilized.

# III. Results

## A. Quality Assessment Process

We have developed a quality assessment process that elaborates 10 questions about the level of quality of the selected studies, as shown in Table II. Those studies that do not reach a threshold of 70% were not included as a relevant work. A total of 61 studies were analyzed and 30 were selected as relevant studies (31 studies were rejected by not reaching the minimum quality threshold).

## B. Research Question

In this work, we investigate four research questions that encompass the models, approaches, tools, and accuracy of ABM for SoS domains. The classification and distribution of the selected studies are depicted in Tables V,VI, and VII. All these questions establish a set of solutions that benefit the usage of agents in the modeling and simulation of SoS.

*1) Research Question no.1*
: RQ01 addresses the nature of an agent-based model to be employed to perform SoS simulations. We classify these models into 6 categories: (i) simulation models for SoS design purposes, which consists of models able to represent one or various aspects of SoS engineering; (ii) simulation models for SoS evolution purposes, which consists of models that deal with the investigation of the evolution process of a SoS; (iii) simulation models for SoS performance purposes, which consists of models able to evaluate the performance of a SoS; (iv) simulation models for SoS optimization purposes, which consists of making the agent-based SoS simulation more robust and efficient; (v) simulation models for SoS theory purposes, which consists of modeling aspects as emergent behavior, independence, evolutionary development, heterogeneity, among other theoretical elements of SoS; and (vi) simulation models for specific domains purposes, which consists of models that serve to investigate various aspects of distinct application domains. We see this result as an increasing necessity of science to better understand a given domain and how this domain operates by applying ABM with SoS.

TABLE IV: Identification of the 30 selected studies in this SLR

| ID | Study Title | Ref |
|---|---|---|
| S01 | "A framework for designing policies for networked systems with uncertainty" | [36] |
| S02 | "Agent-Based Simulation Model for Assessment of Financing Scenarios in Highway Transportation Infrastructure Systems" | [31] |
| S03 | "Assessing the Impact of In-Government Cooperation Dynamics: A Simluation-Based Systems Inquiry" | [20] |
| S04 | "Performance Assessment in Complex Engineering Projects Using a System-of-Systems Framework" | [46] |
| S05 | "System-of-systems modeling and simulation of a ship environment with wireless and intelligent maintenance technologies" | [27] |
| S06 | "Agent-based modeling of climate policy: An introduction to the ENGAGE multi-level model framework" | [14] |
| S07 | "An agent-based dynamic model for analysis of distributed space exploration architectures" | [38] |
| S08 | "A multi-paradigm approach to system dynamics modeling of intercity transportation" | [24] |
| S09 | "ABC+: Extended Action-Benefit-Cost Modeling with Knowledge-based Decision-Makingcand Interaction Model for SoS Simulation" | [19] |
| S10 | "Modeling and simulation of multi-UAV, multi-operator surveillance systems" | [18] |
| S11 | "Stimuli-SoS: a model-based approach to derive stimuli generators for simulations of systems-of-systems software architectures" | [16] |
| S12 | "Revisiting The Meaning of Of as a Theory for Collaborative System of Systems" | [2] |
| S13 | "Exploring the synergy between industrial ecology and system of systems to understand complexity a case study in air transportation" | [11] |
| S14 | "A System-of-Systems perspective for information fusion system design and evaluation" | [37] |
| S15 | "ADS-B and CPDLC fault modeling for safety assessment in a distributed environment" | [41] |
| S16 | "An agent-based modeling approach to creating more resilient littoral combat architectures" | [4] |
| S17 | "Exploring human factors effects in the Smart Grid system of systems demand response" | [30] |
| S18 | "MBA: A system of systems architecture model for supporting collaborative work" | [42] |
| S19 | "Multi-agent system of systems to monitor wildfires" | [15] |
| S20 | "An Analytic Portfolio Approach to System of Systems Evolutions" | [10] |
| S21 | "Capability-Based Quantitative Technology Evaluation for Systems-of-Systems" | [5] |
| S22 | "Formation of Collaborative System of Systems Through Belonging Choice Mechanisms" | [1] |
| S23 | "Modelling provenance collection points and their impact on provenance graphs" | [13] |
| S24 | "A Framework of System of Systems Design with Scenario, Multi-Agent Simulation and Robustness Assessment" | [35] |
| S25 | "Agent-based modeling for smart grid: Application to consumer reaction to demand response" | [25] |
| S26 | "An Agent Based Model of the System of Electricity Production Systems : Exploring the Impact of CO2 Emission-Trading" | [7] |
| S27 | "Framework for understanding and shaping systems of systems: The case of industry and infrastructure development in seaport regions" | [34] |
| S28 | "Multi-agent Architecture with Space-time Components for the Simulation of Urban Transportation Systems" | [33] |
| S29 | "Multilevel Agent-Based Modeling of System of Systems" | [40] |
| S30 | "OSM: an evolutionary system of systems framework for modeling and simulation" | [43] |

TABLE V: Identified studies by category in RQ01 and RQ02

| **Models** | **Studies** | **Freq.** |
|---|---|---|
| Specific domains | (S02, S05, S06, S08, S10, S13, S14, S17, S21, S25, S26, S28) | 40.00% |
| SoS design | (S09, S23, S24) | 10.00% |
| SoS evolution | (S07, S16, S18, S27, S30) | 16.66% |
| SoS theory | (S12, S22, S29) | 10.00% |
| SoS optimization | (S01, S20) | 06.66% |
| SoS performance | (S03, S04, S11, S15, S19) | 16.66% |
| **Approaches** | **Studies** | **Freq.** |
| Scheme | (S15,S25) | 15.38% |
| Architecture | (S07, S16, S18) | 23.07% |
| Technique | (S08,S13) | 15.38% |
| Method | (S03, S17, S18, S20, S21) | 38.46% |
| Mechanism | (S11) | 07.69% |

*2) Research Question no.2*

: RQ02 considers the types of approaches that are utilized to perform ABM-SoS simulations. These results highlight the importance of developing methods and architectures to enhance agent-based SoS simulations. While methods must be utilized to support all the process of SoS engineering, architectures must be investigated to enable a more complex composition of systems that follow a goal in common. Note that methods or methodologies are more robust to represent or to support domain-specific applications. On the other hand, architectures are a key piece to enable the evolution of SoS by defining how each constituent system must be integrated in a SoS over time.

*3) Research Question no.3*

: RQ03 identifies which tools are utilized to perform agent-based SoS simulations in various application domains. We highlight two types of tools: (i) frameworks that must be utilized to reduce the development time of a modeler and to support SoS simulations; or (ii) simulators that must be utilized to run agent-based models into a SoS-enabled platform.

*4) Research Question no.4*

: RQ04.1 addresses which application domains have been investigated in the papers selected through this SLR. We divide into two classes of domains: (i) macrodomains, composed by the general field of each analyzed study; and (ii) microdomains, composed by the mains topics considered in each macrodomain.

Both classes illustrate application domains found through this research protocol. The variety of problems stated by the selected studies demonstrate the capacity that ABMs have on representing SoSs in various issues.

## IV. Literature Review

In this section, we discuss how each selected study identified by the **RQ4.1** has contributed to solve current problems that involve the modeling and simulation of SoS-related systems. We utilize the target problems in SoS identified in the **RQ4.1** to organize this literature review. Also, we contrast these selected works with other well-known methods for integration of complex systems in order to better understand the capacity of using SoS to perform this integration into heterogeneous systems.

### *A. ABM and SoS-Related Complex Domains*

The authors in [27], [11], [33], [38], and [37] have utilized ABM as a technique to model and to simulate SoS-related do-

TABLE VI: Identified studies by category in RQ03

| Frameworks | Studies | Freq. |
|---|---|---|
| Not Identified | (S03,S05,S09,S10,S12,S17, S18,S22,S23,S25,S28,S29) | 40.00% |
| Constructive Sim. Framework | (S21) | 03.33% |
| CVaR Conceptual Framework | (S20) | 03.33% |
| DAF Framework | (S14,S15,S16) | 10.00% |
| Eclipse Modeling Framework | (S11) | 03.33% |
| ENGAGE Framework | (S06) | 03.33% |
| EPSoS Framework | (S04) | 03.33% |
| Exploration-Orienled Framework | (S07) | 03.33% |
| IE/SoS Joint Framework | (S13) | 03.33% |
| Knowledge Feedback Framework | (S26,S27) | 06.66% |
| Multi-paradigm Framework | (S08) | 03.33% |
| OSM Framework | (S30) | 03.33% |
| Policy-Related Framework | (S01,S02) | 03.33% |
| SoS Design Framework | (S24) | 03.33% |
| ROPE Conceptual Framework | (S19) | 03.33% |
| **Simulators** | **Studies** | **Freq.** |
| Not Identified | (S07,S13,S17,S21,S25) | 16.66% |
| AnyLogic Simulator | (S02,S04) | 06.66% |
| ENGAGE Simulator | (S06) | 03.33% |
| GAMA Platform | (S10,S28) | 06.66% |
| MADKiT Simulator | (S29) | 03.33% |
| MATLAB Simulator | (S05,S14,S15,S16,S19,S20) | 20.00% |
| NetLogo Simulator | (S01,S12,S22,S23) | 13.33% |
| OMAS Platform | (S18) | 03.33% |
| OSM Java-Based Simulator | (S30) | 03.33% |
| REPast Simulator | (S26,S27) | 06.66% |
| SEAS Military Platform | (S03) | 03.33% |
| SimVA-SoS Simulator | (S09) | 03.33% |
| MS4ME Engine | (S11) | 03.33% |
| ABM/SD Simulator | (S08) | 03.33% |
| SoS Design Simulator | (S24) | 03.33% |

TABLE VII: Domains and Identified Problems in RQ04

| Macrodomains | Studies | Freq. |
|---|---|---|
| Chemistry | (S12,S22) | 06.66% |
| Energy | (S17,S24,S25,S26) | 13.33% |
| Healthcare | (S23) | 03.33% |
| Infrastructure | (S02,S27) | 06.66% |
| Projects | (S04,S18) | 06.66% |
| Public administration | (S03,S06,S09,S11,S19) | 16.66% |
| SoSe | (S30) | 03.33% |
| Space Exploration | (S07) | 03.33% |
| Transport | (S01,S08,S13,S15,S28,S29) | 20.00% |
| Warfare | (S05,S10,S14,S16,S20,S21) | 20.00% |
| **Microdomains** | **Studies** | **Freq.** |
| Air Transportation | (S13, S15) | 06.66% |
| Chemical Reactions | (S12, S22) | 06.66% |
| Disaster Management | (S19) | 10.00% |
| Electricity Production | (S26) | 03.33% |
| Engineering Projects | (S04) | 03.33% |
| Fighter Aircraft | (S21) | 03.33% |
| Healthcare Systems | (S23) | 03.33% |
| Human Behavior | (S03, S17, S25) | 10.00% |
| Logistics | (S29) | 03.33% |
| Mass-Casualty Incident | (S09, S11) | 06.66% |
| Naval Technology | (S05,S16, S20) | 10.00% |
| Policies | (S01, S02, S06, S24) | 13.33% |
| Software Projects | (S18) | 03.33% |
| SoS Evolution | (S27, S30) | 06.66% |
| Spacecraft Technology | (S07) | 03.33% |
| Surveillance | (S10, S14) | 06.66% |
| Urban Transportation | (S08, S28) | 06.66% |
| **Target Problems in SoS** | **Studies** | **Freq.** |
| Domain modeling issues | (S05,S07,S08,S13,S14,S28) | 20.00% |
| Social issues | (S03,S10,S17,S25) | 13.33% |
| Optimization issues | (S01,S19,S20) | 10.00% |
| Performance issues | (S04,S15,S16,S21,S26) | 16.66% |
| Policy issues | (S02,S06,S24) | 10.00% |
| SoS Engineering issues | (S09,S11,S18,S23,S27,S30) | 20.00% |
| SoS Theoretical issues | (S12,S22,S29) | 10.00% |

mains with high level of complexity. For example, in S05 [27], they investigate decision processes in Navy Warfighters by proposing a model that incorporates components of a ship such as machinery, equipment consuming power, crew mobility, among others. The results demonstrate that the development of intelligent maintenance systems positively influence in machine availability. In S13 [11], the authors investigated how a network performs changes over time in air transportation through patterns in the behavior of agents and its implications for decision makers. An illustrative scenario was investigated by simulations. The results highlighted the emergent behavior from combined actions between airlines and terrestrial providers such as airports or governmental agencies.

In S28 [33], a SoS simulator is developed to simulate regulatory strategies in transportation systems. They utilized a multi-agent based modeling to analyze urban transportation policies. The authors investigated the displacement of people in the city of La Rochelle. The results indicate the tool is effective to analyze the behavior of users in urban transportation systems. In S07 [38], the authors explore architectures for networks of resources across the solar system. They utilize SoS to define time-varying performance measures and agent-based modeling to simulate the evolution of these architectures. A proof-of-concept is developed by utilizing a solar system mobility network. Results suggest the SoS agent-based simulation can assist architectural designs of further space explorations. In S14 [37], it was developed a SoS able to represent an Information Fusion System (IFS) by utilizing multi-agents and Design of Experiments for evaluating objectives of the design space of this system. The authors employed the Discrete Agent Framework (DAF) to simulate the IF-SoS model. The results enforce the accuracy of SoS as a paradigm that enhances the development of these kinds of system.

An alternative to model all the complexity and integration of systems is to combine ABM with other well-known techniques. In that way, the authors in S08 [24] have developed a simulation framework for transportation systems that arranges ABM with the systems dynamics technique. They have stated that predicting demand in this domain is a challenging task due to high level of mobility existing between their interacting systems. In this case, the combined model must consider aspects as the flow of US travelers that choose different vehicles, routes, infrastructure, suppliers as airlines or intercity buses, manufacturers and government. Each transportation system is considered as a constituent of a SoS and simulation models (e.g. the MI and GAME models) are applied to understand the multimodal transportation demand in US, enabling novel policies and technologies to be rightly elaborated and deployed in this kind of scenario. The simulation results indicate that combining ABM with other techniques is a feasible way to interpret SoS-based systems.

### B. ABM and SoS-Related Social Aspects

The authors in [20], [18], [30], [25] have utilized ABM to better understand social factors in SoS. For example, in S03 [20], the authors establish a set of canonical forces to understand how government organizations (called GEE or government extended enterprise) interact to benefit the society. In that sense, GEE are autonomous government organizations that must cooperate with other agencies to reach in-common missions. They investigate forces that affect GEE cooperation and SoS operation, and state that such forces influence the behavior of these organizations into scenarios with uncertainties. Such organizations are combined into a SoS where employees and employers cooperate. The behavior and human cooperation among these organizations is investigated through a case study about decision-making of a north-American government agency in relation to a bomber at the Christmas Day. According to the authors, ABM was effective to demonstrate the relevance of using ABM to represent the dynamics of social cooperation.

The following works investigate how humans can influence the performance of complex systems. For example, the authors of S10 [18] have proposed a SoS agent-based modeling for surveillance systems that utilize UAVs and operators to understand the relation between humans and machines. They proposed a model that predicts the capability of these systems by sizing the involved humans, the involved UAVs, and level of autonomy. The results serve as a reliable reference for engineers to perform their predictions about the performance of this kind of SoS. In S17 [30], the authors investigated the influence of human factors in the behavior of a collaborative SoS. The authors developed an illustrative scenario called the smart grid demand response. The results reveal that human factors can influence the performance of SoSs through new stories and human interactions. In S25 [25], the authors designed a simulation with ABM and other simulation techniques to investigate the performance of Smart Grid. They utilized SoS to understand the efficiency of these systems and their sustainability. A sample Demand Response scheme was simulated to check interactions between agents and environment. The results indicate the effectivity of ABM to model and to simulate Smart Grid systems.

### C. ABM and SoS-related optimization Approaches

The authors in [36], [15], and [10] implement approaches that optimize the performance of SoS in distinct scenarios such as policies, emergence events, and finance domains. For example, the authors of S01 [36] develop a framework that builds surrogate models and investigates the stability of dynamic systems to enhance policies for networked systems. They have performed a simulation using the transportation network benchmark problem. The results illustrate the efficiency in policy optimization under uncertainty to solve problems related to traffic grid policy designs. In S19 [15], ABM and SoS are used to investigate the problem of wildfires. They develop a collaborative SoS to increase the accuracy and robustness of locating and tracking the spread of wildfires. The authors simulated some illustrative scenarios to predict the behavior of fire-detecting configurations. Results indicate that the collaborative SoS outperforms the traditional approach to track wildfires. In S20 [10], the authors propose an approach to manage risks through a perspective called Conditional Value-at-Risk (CVaR). Data from agents are simulated to better identify capabilities, costs, and operational risks from portfolios of systems. The authors utilized a naval warfare as an illustrative scenario. The results demonstrate the optimization of portfolios is a feasible alternative for managing SoS architectural development.

### D. ABM and SoS-related performance issues

The authors in [46], [41], [4], [5], and [7] have proposed works that evaluate the performance of SoS into complex scenarios such as engineering projects, European aerospace, naval warfare, US air force, and Dutch electricity sector. In S04 [46], a SoS framework is developed to evaluate the performance of complex engineering projects. This framework incorporates base-level abstraction and multilevel aggregation. A case study about a construction project is presented. The results indicate the success of this tool to better understand the performance of these kinds of engineering projects. In S15 [41], it is investigated how faults in technologies such as Automatic Dependent Surveillance-Broadcast (ADS-B) and Controller Pilot Data Link Communication (CPDLC) can negatively impact in the Next Generation Air Transportation System (NextGen). They investigate which are the main types of failures in electronics devices of aircrafts through ABM simulations. The simulation results identify faults that degrade the safety of this kind of system.

In S16 [4], the authors develop an evaluation tool that identifies resilient SoS architectures that perform well even if there are network failures and attacks. A networked naval warfare scenario is simulated by considering the SoS theory. The results demonstrate the accuracy of SoS combined with agent-based models to define potential architectures for such threats and disruptions. In S21 [5], the authors have employed physics models of an aircraft system, neural network surrogate and agent-based models for constructive military simulations. A simulation is performed to evaluate a Long Range Strike air vehicle and system architecture from the US Air Force. The results reveal that surrogate and agent-based models are effective to accelerate processes and simultaneously evaluate capability-focused technologies into aeronautical scenarios. In S26 [7], the authors employed an agent-based modeling to investigate the impact of CO2 Emission-Trading (CET) in the Dutch electricity sector. The simulation results indicate that the impact of CET is small, although a long time is necessary to materialize it.

### E. ABM and SoS simulations for policy issues

The authors in [31], [14], and [35] have investigated how ABM and SoS can create insights about generation of policies. For example, in S02 [31], the authors developed an ex-ante analysis of microbehaviors of private and public entities to investigate how financing policies affect investment in infrastructure of U.S. highway transportation. A simulation was performed to visualize impacts of these policies. The results illustrate the importance for highway transportation policymakers at utilizing this tool as a way of analyzing policies that consider impacts and uncertainties. In S06 [14], the authors develop the framework ENGAGE to simulate international agreements and domestic policies about climate changes. They utilize a game theory-based approach called PUTNAM to perform SoS simulations. The results demonstrate that ENGAGE is an accurate tool to evaluate policies that consider agent decision-making and social / technological contexts. In S24 [35], the authors developed a framework for dealing with SoS designs. They investigate dynamics of a design space, how emergent is the behavior between constituent systems, and their unpredictability. The authors presented a case study about how to develop policies for improving the energy generation. The results indicate that the framework is effective for SoS designers to choose better design options of a SoS.

### *F. ABM and SoS Engineering-Related Issues*

The authors in [19], [16], [42], [13], [34], and [43] have investigated how ABM could model and simulate SoS engineering aspects. In this sense, in S09 [19], the authors develop a model called ABC+ that adds internal knowledge in a CS and communication between CSs to analyze SoS behaviors. A case study was performed to enhance SoS-level behavior simulation. The results demonstrate that the addition of internal knowledge and communication between CSs improve the SoS performance, being ABC+ an accurate model for understanding the behavioral dynamics of a SoS. In S11 [16], the authors propose a model-based approach called Stimuli-SoS that creates stimuli generators to reduce the level of human intervention in SoS simulations. A case study is developed about a SoS model of flood monitoring to monitor rivers that cross urban areas. The results indicate that Stimuli-SoS is effective to automatically generate specific data in SoS simulations. In S18 [42], the authors propose a model called Memory Broker Agent (MBA) to improve interoperability between constituent systems of a SoS. The authors developed a case study about how to enhance code quality in the software industry. The results demonstrate that MBA architecture enables the development of a SoS with robustness, flexibility, and semantic interoperability thus easing collaboration between development teams.

In S23 [13], the authors propose a simulation tool that identifies the amount of provenance captured by a SoS. A case study about the US healthcare system is introduced to anticipate areas in provenance capture. The results indicate that it is possible to capture provenance within SoS since the tool changes the interactions among the constituent systems and types of capture. In S27 [34], the authors develop a framework to investigate industry-infrastructure in seaport regions. This framework is composed by ontologies, employees, associations, infrastructure, knowledge feedback process, and service modular agent based model. A case study about a business biobased cluster evolution in the Eemsdeltac (Netherlands) was developed. The results can be utilized as feedback to the knowledge process. In S30 [43], a framework called Orchestrated Simulation through Modeling (OSM) is proposed to enable the insertion of plugins developed by third parties to form a robust SoS system. The authors employed a case study about Predator/Prey that utilizes a single model plug-in to characterize the evolution of a SoS. The results indicate that OSM is an effective framework that eases the collaboration between developers.

### *G. ABM and SoS Theoretical Aspects*

The authors in [2], [1], and [40] have investigated how ABM could simulate aspects of the SoS theory. In S12 [2], the authors investigated the Boardman & Sauser SoS theory [3] through a model of chemical reactions with formation of molecules from atoms to better understand how collaborative aspects could operate into a SoS. A simulation was conducted to evaluate the behavior of these chemical reactions. The results indicate that the simulation was essential to better understand aspects associated to health, maintenance, replication, and evolution of SoSs. The authors of S22 [1] develop a collaborative SoS to understand its evolution. Properties are mathematically modeled. An ABM simulation is developed to validate the model based on chemical reactions. The results can be utilized by engineers to improve the formation and management of SoS. In S29 [40], the authors created a generic multilevel multi-agent formalism that represents and controls the complexity of a SoS. A combination of models is utilized to deal with dynamic and static aspects of SoS. The authors developed a case study about autonomous vehicles to automate the port container logistic. The results indicate that the formalism based on SoS is effective for representing autonomous vehicular scenarios.

### *H. Alternatives to SoS*

The authors in [26], [44], [6], and [45] have developed an alternative theory about how integrating complex systems. The authors in [26] investigate critical infrastructure for oil and gas. This work interprets the interdependence and interconnection of networked critical infrastructures as a risk factor to potential cascading failures since overloads, terrorist attacks, or other types of situation could disrupt the operation of all the interconnected infrastructures. To better understand this problem, the authors have applied a tool called social network analysis, which investigates human interactions to infer aspects of this network. This analytical tool analyzes how members in a given social network establish relations with others networks. According to these authors, critical infrastructures have similar interactions to humans (i.e. the interaction between networks could be unidirectional or peer-to-peer). They investigate Canadian critical infrastructures to improve the capacity of policymakers into identifying suitable protection for such critical infrastructures. The authors in [44], [45] detail concepts about the model called Function-Behavior-Structure. This model can be utilized for designing Complex Systems. They have defined a framework called FBPSS and is utilized in each autonomous system from the Canadian critical infrastructure. This model is effective and could be utilized jointly with SoS to represent heterogeneous systems.

## V. Concluding Remarks

This work has conducted a systematic literature review to identify how agent-based models are employed to simulate systems-of-systems. We have identified which are the most utilized application domains as well as which methods, approaches, and tools have been extensively utilized to simulate these kinds of systems. We have interpreted the findings of this review as an opportunity for researchers, industry developers, military, or government players to conduct researches about themes that use such agent-based models for SoS scenarios.

Firstly, little effort has been given to enhance SoS theory-related aspects. We see good opportunities to fulfill this research gap, as for example, investigating how constituent systems can belong to a given SoS, how the emergent behavior appears with the interaction of systems, how a SoS performs collaboration or cooperation between their constituent systems, or how agent-based models could test relevant aspects of SoS theory. Moreover, the industry could perform more agent-based SoS simulations to better understand, for example, the interaction of IoT systems incorporated in the industrial Internet, to shape the evolution of its automation systems, or to analyze events identified in its production systems.

Secondly, we also need to enhance the current SoS simulation tools. The simulators identified do not encompass a large number of frameworks, approaches or models, therefore being risky to perform SoS simulations that need to have all this joint complexity to perform robust simulations. We need to advance in specific programming languages that better represent the features of an agent-based SoS simulation to ease all the process of engineering these complex systems. It is also important to to develop specific researches about the behavior of the different SoS types to enhance the SoS engineering field, since the majority of the selected studies in this review do not specify the type of SoS, an essential information to understand the SoS dynamics.

Thirdly, we need to include advanced statistical analysis in order to have more confidence about data from SoS simulations. The usage of suitable statistical techniques would enable to better understand scientific hypotheses and data gathered from these kinds of simulations. For instance, recent paradigms such as Internet of Things, Internet of Everything, and Internet of Anything encompass interconnected systems (e.g. cyber physical systems, cyber biological systems, and Industrial Internet) that could generate a high amount of data to be statistically processed. Therefore, this is an opportunity for researchers to publish novel advancements in aforementioned promising fields.

Likewise, we glimpse some promising directions that could be explored in future research: (i) Developing simulators that encompass all the theory behind SoS; (ii) Developing methods, tools, or approaches to validate agent-based SoS simulations;(iii) Giving more attention to performance-related issues and optimization in SoS domains; and (iv) Simulating agent-based models by considering the existing types of SoS.

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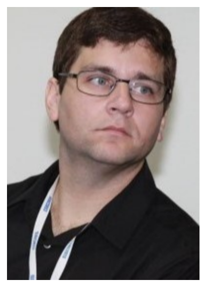


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