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Review article

Agent Based Modelling and Simulation tools: A review of the state-of-art software

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ABSTRACT

The key intent of this work is to present a comprehensive comparative literature survey of the state-of-art in software agent-based computing technology and its incorporation within the modelling and simulation domain. The original contribution of this survey is two-fold: (1) Present a concise characterization of almost the entire spectrum of agent-based modelling and simulation tools, thereby highlighting the salient features, merits, and shortcomings of such multi-faceted application software; this article covers eighty five agent-based toolkits that may assist the system designers and developers with common tasks, such as constructing agent-based models and portraying the real-time simulation outputs in tabular/graphical formats and visual recordings. (2) Provide a usable reference that aids engineers, researchers, learners and academicians in readily selecting an appropriate agent-based modelling and simulation toolkit for designing and developing their system models and prototypes, cognizant of both their expertise and those requirements of their application domain. In a nutshell, a significant synthesis of Agent Based Modelling and Simulation (ABMS) resources has been performed in this review that stimulates further investigation into this topic.

Contents

1. Introduction

Computer modelling and simulation relates to the manipulation of a computational model in order to enhance the analysis of systems' behaviour and to assess strategies for its functioning in the descriptive or predictive modes. The term *model* is considered as "an abstract and simplified representation of a

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given reality, either already existing or just planned. Models are commonly defined in order to study and explain observed phenomena or to foresee future phenomena" [1]. A simulation is the discernible manifestation of a model, represented by a computer program that provides insights about the system or application under investigation. A simulation model refers to the computing algorithms, mathematical expressions and equations that encapsulate the behaviour and performance of a system in the real world scenarios.

An agent is simply regarded as an entity, notion or software abstraction similar to the well known programming specifications such as objects, methods, procedures and functions. An element or object abstraction wraps the methods and attributes of a software module. However, an agent presents a distinctly higher scale software abstraction that defines a complex software unit in an efficient and convenient way. Instead of being expressed in terms of attributes and logic-based methods, a software agent is primarily typified in terms of its intended actions. This is principally a matter of stating agents' responses instead of identifying classes, methods and properties. A suggestion to have a computer programmed agent that can undertake complicated charge on peoples' behalf, is naturally appealing [2]. There are a minimum set of fundamental traits that represent a software agent. "A software agent is autonomous; capable of operating as a standalone process and performing actions without user intervention" [3]. A software agent is responsive and able to converse; it inter-communicates with the user as well as to other software agents or processes. Additionally, an autonomous agent is inherently intuitive; it possesses the ability to perceive and respond to the changes within the surrounding domain [4]. A core characteristic of an agent is its potential to make independent deliberations during the problem-solving, conflict resolution and decision-making processes. An agent-based paradigm can be regarded as an intrinsic extension to object-orientation, whereby an agent represents an object having control on its execution [5]. However, agents are intrinsically more autonomous and proactive than objects. Agent-based methodologies permit the prototype designers to implement the system units with a number of specialized agents having sophisticated intellectual capabilities such as reasoning, learning and planning, thereby incorporating the resource knowledge of the underlying problem domain. Quoting [6], the "Agent metaphor fits perfectly well to the demands of complex and inherently distributed applications, where each agent is a coarse-grained computational system in its own right, as well as independently modifiable".

Agent Based Modelling and Simulation (ABMS) refers to a category of computational models invoking the dynamic actions, reactions and intercommunication protocols among the agents in a shared environment, in order to evaluate their design and performance and derive insights on their emerging behaviour and properties. From a simulation standpoint, an individual component's function can range from very basic 'if-then' reactive rules to a more sophisticated cognitively rich behavioural models. An influential paradigm is that of the BDI (Belief–Desire–Intention) framework for artificial intelligence based multiplexed models [7,8]. BDI terminology recognizes "an agent can be identified as having: a set of beliefs about its environment and about itself; a set of desires which are computational states which it wants to maintain, and a set of intentions which are computational states which the agent is trying to achieve" [9,10]. Valuable reviews of Agent-based programming tools and languages has been provided in the literature [11] and increasingly their application is becoming ever diverse challenging the capabilities of power constrained devices [12–14]. The philosophy of ABMS is to model complex systems adopting a bottom-up approach starting from the individual agents [15]. A concrete approach of ABMS is to model and simulate realistic scenarios with a group of self-governing agents either as simplistic entities inside the computing code-snippets or as considerably intelligent objects. This might possibly be considered synonymous to a human being's problem solving capabilities with infinite states, beliefs, trusts, decisions, actions and responses. Acquiring adequate know-how of the system in order to construct an appropriate conceptual and logical model is one of the most challenging task in the simulation tests.

Over the years, numerous agent-based modelling and simulation tools have been developed each with a somewhat unique motive for its presence. Every strategy marks a specific programming syntax and semantics for the agents and has a differing base concerning the generality, usability, modifiability, scalability and performance. The primary objective of this paper is to provide a comprehensive review of a wide range of agent-based modelling and simulation software packages. Due to differing factors, many of these tools are research artefacts that never transitioned from the academic sphere to the commercial world or have stopped receiving support. However their rich functionality and rich features form an important legacy for the future and therefore they are included in the survey presented within this paper. Web sites of the systems that are discussed in the paper have been archived in the Wayback Machine, a digital log of Internet's information that registers and maintains complete snapshots of all Web-links located under a single domain name [16].

The remainder of the paper is structured as follows. Section 2 reports some related past surveys. Section 3 outlines the implementation and application scope of different relevant platforms for ABMS with regard to modelling capacity or scalability. A comparison together with evaluation criteria, and salient features, merits, limitations of various state-of-art ABMS tools compiled in this review, are discussed in Section 4. Finally, in Section 5, the implications of this research and concluding remarks are presented.

2. Relevant surveys

The importance of the subject has attracted a number of surveys of ABMS tools in recent years focusing on the different aspects of Agent-based Systems (ABS) modelling and simulation. A number of review papers have addressed the specific domains of ABMS application. A survey reported in [17] has attempted to shed light on the landscape of agent designing, modelling and simulation toolkits available in the market focusing on their use in the post-secondary education. Data collection was based on the install and trial use of twenty agent toolkits. The paper concluded that no single consistent package fulfils the needs of entire agent-related curriculum. [7,18] surveyed agent-based simulation packages for the energy consumption markets. Based on this analysis, the papers investigated an agent-mediated simulation framework to facilitate the development of models for electricity markets. [19] portrayed previous online reviews on a number of ABMS packages and outlined challenges that should be met in order to realise ABMS a mainstream technology in the computational science domain. [20] evaluated how ABMS packages can offer any value-addition in the modelling/simulation of the highly complex peer-to-peer network systems. [21] discussed ABMS as a proven powerful tool for studying and analysing the dynamics of consumer market-place. [22] provided a survey pertaining to a selection of ABMS systems (Swarm, MASON, Repast, StarLogo, NetLogo, OBEUS, AgentSheets and AnyLogic) with particular reference to the development of geospatial simulations.[1] described the typical elements of an agent-based simulation model and included results of their investigation on a couple of accessible ABMS toolkits. In [23], the authors have categorized various characteristics of the agent development and simulation toolkits into user-friendly

Table 1
Comparison of various agent based modelling and simulations (ABMS) tools.

ABMS Software Tool -------------------- License / Availability	Source Code	Type of Agent based on its Interaction Behaviour	Coding Language or Application Programming Interface (API) for Model Development -------------------- Integrated Development Environment (IDE)	Compiler -------------------- Operating System (OS) -------------------- Implementation Platform	Model Development Effort	Modelling Strength / Simulation Models' Scalability Level	ABMS Scope or Application Domain
Agent Cell http://www.agentcell.org https://sourceforge.net/projects/agentcell/ ---------------------- Open source, GPL Uses Repast (BSD) multi-agent framework and StochSim-1.4 (LGPL) as foundation, Free	Java	Reactive agents	Java ------------------------ IDE: Eclipse	Java Runtime Environment -------------------- Linux -------------------- Personal computer and large-scale scientific computing clusters	Complex/Hard	High/ Large-scale	2D/3D simulations to study the interlinks among the behaviour of individual cells and stochastic intracellular processes
Agent Factory http://agentfactory.ucd.ie/index.php/Main_Page ---------------------- Open source, LGPL, Free	Java	Mobile, Reactive, Belief-Desire-Intention (BDI), Bespoke, and Deliberative agents	Java ------------------------ IDE: Eclipse + Visual intuitive graphical tools to support the design of agents	Any Java-enabled platform -------------------- Laptops, desktops, and servers, Agents can also be deployed on constrained handheld things such as mobile phones and sensor devices	Moderate	High/ Medium-scale	Rapid prototyping, visualisation, testing, debugging, and deployment of multi-agent based systems for social network analysis
AgentScript http://agentscript.org/ ---------------------- Open source, GPLv3, Free	Java	Turtles or active objects (with simple goals) implemented as class constructs	Model libraries & add-ons available ------------------------ CoffeeScripts directly within the browser	Models' ouptput printed to the "JavaScript console" on running -------------------- Windows, Mac OS X, Linux, Unix, Runs on any Java virtual machine -------------------- Desktop computer, Smart tablets	Simple/Easy	Light-weight / Small-scale	Minimalist ABMS framework (based on NetLogo agent semantics) for social sciences, education/learning
AgentSheets http://www.agentsheets.com/ ---------------------- Closed source, Proprietary, Trial version available	Java	Reactive Behavioural agents	Visual AgenTalk® ------------------------ Visual drag drop, conversational programming interface allows the creation of easy-to-understand programs	Java Runtime Environment -------------------- Windows, Mac OS X, Linux, Unix, Runs on any Java virtual machine -------------------- Desktop computer	Simple/Easy	Small-scale ~ Medium-scale	Teaching agent-based based simulations to students in social studies, mathematics, natural sciences, social sciences
Altreva Adaptive Modeler http://www.altreva.com/ ---------------------- Closed source, Proprietary, Free evaluation version available for research & experimentation (rare limitations but no expiration)	Microsoft .Net	Reactive, Evolutionary agents	Visual model development, easy to use drag-and-drop user interface, real-time charts and plots to visualise model evolution, behaviour, and performance, user configurable genetic programming engine for trading rules creation	Microsoft.Net Framework 2.0 or higher -------------------- Windows 7, Vista, XP, 2000 or NT 4.0 -------------------- Desktop computer	Simple/Easy	High/ Large-scale Agent-population max. 100,000	Financial market's simulation models for the purpose of forecasting prices of real world market traded stocks or securities

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taxonomies. This survey has focused mainly on the platforms that are solely used for the agent design and construction purposes and has neglected the issues related to their simulation capability. Moreover, [23] compared quite a few freely available agent-based computer programming libraries to find out the modelling framework that is best suited for the theory, and practice or data-based simulation of social sciences. The rating results determine RePast to win out over the other social simulation tools in terms of modelling effort and time consumed.

Other comprehensive surveys were reported in [11,19,24–28]. In [29], five platforms (NetLogo, MASON, Repast, Java Swarm, Objective-C Swarm) widely used for agent-supported modelling and simulation applications, were compared. This article identified future priorities around the adoption of agent-based platforms that

Table 1 (*continued*)

AnyLogic http://www.anylogic.com/ ---------------------- Closed source, Proprietary, Free personal learning edition available	Java	Agents/ objects implemented as Java classes	Java; UML-RT (UML for real time) ------------------------ User-friendly graphical environment for visual model development	Java Runtime Environment -------------------- Windows 7 & Vista, Mac OS X, Linux ------------------- Desktop computer	Moderate	High/ Large-scale	Interactive 2D/3D simulations in manufacturing, business strategy & innovation analysis, transportation, healthcare, social sciences, economics, urban dynamics, supply chains, computer/telecom networks, logistics, warehousing, power grids, complex adaptive dynamic/discrete-event systems
AOR Simulation (Agent-Object-Relationship) http://oxygen.informatik.tu-cottbus.de/aor/ ---------------------- Open source, GPL, Free	Java	Cognitive agents that maintain their own beliefs about the objects in their environment (in the form of belief triples)	Java; Java-script	Java Runtime Environment -------------------- Windows, Mac OS X, Unix, Linux, Web -------------------- Desktop computer	Moderate	High/ Large-scale	Agent-based/ discrete-event simulations (management, social sciences, economics, biology)
Ascape http://ascape.sourceforge.net/ ---------------------- Open source, BSD, Free	Java	Agents/ objects implemented as Java classes	Models library's built-in routines available ------------------------ Java ------------------------ IDE: Eclipse or IntelliJ	Any Java-enabled platform -------------------- Desktop computer	Moderate	Medium-scale ~ Large-scale	General-purpose modelling and simulation (social science, evolutionary game theory, organizational processes, economics, anthropology, sociology political science)
BehaviourComposer http://m.modelling4all.org/ http://resources.modelling4all.org/Home ---------------------- Open source, BSD, Free	Java --------------- Built upon Google Web Toolkit and NetLogo	Prototype agents having scheduler conditions & actions defined by the commands	Models library consisting of modular code fragments: micro-behaviours (independent processes, threads or repeatedly scheduled events) available ------------------------ Ajax (JavaScript and XML), NetLogo programming language (can use extensions API thereby making calls to Java-based routines) ------------------------ User-friendly environment for visual model development	BC2NetLogo program enables to build models in Behaviour-Composer and to run them in NetLogo -------------------- Within any Java-enabled platform, also runs as an applet in a Web-browser -------------------- Windows, Unix, Linux, Mac OS X -------------------- Desktop computer, Smart tablets	Simple/Easy	Small-scale ~ Medium-scale	2D/3D basic simulations in social/natural sciences (such as predatory-prey system, social networks and vaccination, Zoology, business studies, epidemics, Sugarscape, etc.) for teachers, researchers and learners
Brahms http://www.agentisolutions.com/brahms.htm ---------------------- Open source, Freely available for academic & research purposes	Java	Cognitive, Belief-Desire-Intention (BDI) agents	Brahms API is an agent/object-oriented BDI language. Brahms is completely integrated with the Java programming language; Brahms and Java agents can interact together. BVM (Brahms Virtual Machine) is a multi-agent/discrete-event engine that runs each agent as a Java thread ------------------------ IDE: Eclipse or Brahms Composer	Java Runtime Environment -------------------- Windows, Linux, Solaris, Mac OS X -------------------- Desktop computer	Complex/Hard	High/ Large-scale	Multi-agent based system to model and simulate people's activity and situated behaviour (location, artifacts, communication, etc.) and collaboration/ coordination (complex work practices) in organizational processes

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seem likely to make these aforementioned software more fruitful for the ABMS research and development. [30] provides an overview of the popular platforms, surveyed approaches and systems for the parallel and distributed simulation of agent-based systems, outlining future challenges in the design of such platforms. A survey of parallel simulation toolkits was also provided in [31].

Although these surveys provide useful insights into the different systems available for agent-based systems' modelling and simulation, they are outdated and far from complete. Besides covering ABMS tools, these efforts do contain some platforms that are more generally used for agent design, construction and modelling purposes, but have no specific simulation functionalities. In con-

Table 1 (*continued*)

Breve http://www.spiderland.org/ ---------------------- Open source, GPL, Free	C++ ----------------- OpenGL	Stimulus-responsive simple mobile agents	A collection of built-in open source libraries to create models ------------------------ Breve simulations in popular Python coding; or an easy-to-use object-oriented language 'Steve' that borrows many features of C, Objective C, Smalltalk, Perl languages ------------------------ Breve IDE: Simulation code editor	Mac OS X, Linux, Windows -------------------- Desktop computer	Moderate	Medium-scale	Builds 3D simulations of agent-based systems representing artificial life
BSim http://bsim-bccs.sourceforge.net/ ---------------------- Open source, OSI-MIT License, Free	Java	Reactive Behavioural agents	Java ------------------------ IDE: Eclipse	Java Runtime Environment -------------------- Windows, Unix, Linux, Mac OS X -------------------- Desktop computer	Complex/Hard	High/ Large-scale	Simulations in 2D/3D related to: stochastic interactions of bacterial populations and particles in a fluids, multi-cellular computing in synthetic biology
CloudSim http://www.cloudbus.org/cloudsim/ ---------------------- Open source, Free, GNU Lesser GPL	Java	Logic of agent/objects implemented as policies for cloud provisioning, scheduling, migration	Java ------------------------ IDE: Eclipse	Mac OS X, Linux, Windows -------------------- Desktop computer	Moderate	Large-scale	Modelling and simulation of cloud computing / virtualised datacentre based infrastructures and services
Cormas (COmmon-pool Resources and Multi-Agent Simulations) http://cormas.cirad.fr/ ---------------------- Open source, Free, Cormas users' charter	Smalltalk (VisualWorks® Cincom Systems)	Agents/ objects implemented as class constructs	Smalltalk	VisualWorks® from Cincom Systems -------------------- Windows, AIX, Solaris, Linux, Mac OS X -------------------- Desktop computer	Moderate	Medium-scale	Simulations of natural renewable resource management, geographic information systems, marketing, ecology
CRAFTY (Competition for Resources between Agent Functional TYpes) http://crafty-abm.sourceforge.net/ ---------------------- Open source, Free	Java	Configurable spatial data structures as objects (cells/regions) with different production functions in thresholds, Component role- based agents	R code for creating and writing rasters & model configurations ------------------------ IDE: Eclipse (install MecurialEclipse in Eclipse in order to use the Bitbucket repository)	Templates (Basic, Social, CoBRA) -------------------- Mac OS X, Linux, Windows -------------------- Desktop computer, Workstation	Moderate	Medium-scale ~ Large-scale	Simulations of a wide range of land uses and logistics (goods/services)
CybelePro http://i-a-i.com/cybelepro/ ---------------------- Open source, Proprietary, Academic licenses available on discount	Java	Reactive agent/objects implemented as Java classes	Java-based CybelePro API ------------------------ MDLe (Motion Description Language Extended) for creating high-level platform independent plans for robots ------------------------ IntelliTrace for performing post-run analysis and visualization of multi-agent simulations	Java 1.4.2 or higher -------------------- Windows, Linux, Solaris, Mac OS X, Java-1.4-capable PDAs -------------------- Desktop computer	Moderate	High/ Large-scale	Modelling and simulations of high-performance infrastructures and large-scale distributed systems (such as robotics, planning & scheduling, communication network systems and cross-enterprises, data-mining, control of air and ground transportation systems)

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trast, this paper covers a wide range of the state-of-art ABMS software addressing, not only the modelling, but also simulation capabilities. Several special traits of agent-based software are highlighted that are not covered in any of the previous surveys. The review covers a broad range of prevalent ABMS software tools (eighty five tools are discussed) providing information about the agents' types that can potentially be implemented in each tool, and meticulously extracting the overall finer details from the documentation or user–guides of each individual tool. The basic features, attributes and relative comparison among various tools have been structured in a comprehensive and intelligible tabular and chart formats.

Table 1 (*continued*)

D-OMAR (Distributed-Operator Model ARchitecture) http://homepages.sover.net/~nichael/nlc-publications/lugm98/domarfinal.htm --------------------- Closed source	Lisp (Server-side), Java (Client-side), D-OMAR's Middle-ware layers: Java RMI, HLA, CORBA (C++)	Cognitive agents	SCORE (a procedural language); Simple Frame Language (SFL); D-OMAR's rule language ------------------------ D-OMAR's simulation developer interface (Concept Editor)	Sun/Sparc, Windows, (WNT/W98), Mac OS X -------------------- Graphics workstation	Complex/Hard	Large-scale	Simulation development environment designed to explore and model human multiple task-based behaviours (air-crew/ air-traffic control and communication)
DigiHive http://digihive.pl/ ---------------------- Closed source, Free	C++ in Microsoft Visual Studio's Integrated Development Environment	Evolutionary agents	Prolog	GTK Runtime Support -------------------- Windows, Unix, Linux -------------------- Desktop computer	Complex/Hard	Medium-scale	Simulations of artificial life, emergent phenomena, self-adaption, self-replication
Echo http://tuvalu.santafe.edu/projects/echo/ --------------------- Open source, Free	C language (implemented on Sun Sparc architecture using Sunos-4.1.3)	Adaptive Evolutionary agents	C ------------------------ IDE: Eclipse-CDT for Echo-1.3 ------------------------ Windows user interface available for Echo-1.1	X Windows System -------------------- Linux, Unix-BSD -------------------- Desktop computer, Workstation	Complex/Hard	High/ Large-scale	Simulation environments for complex adaptive systems, ecological modelling, etc.
EcoLab http://ecolab.sourceforge.net/ --------------------- Open source, Free	C++	MPI-based agents implemented as C++ classes	C++'s Standard ClassDesc and Graphcode libraries available ------------------------ Scripting language C++/TCL (Tk and BLT widgets for GUI-mode) ------------------------ IDE: Eclipse-CDT	Windows, Linux, Unix, Mac OS X -------------------- Desktop computer, Workstation, and large-scale parallel computing clusters	Complex/Hard	High/ Large-scale	Simulations of complex dynamics of evolution
Envision http://envision.bioe.orst.edu/ --------------------- Open source, Free	Microsoft Visual C++	Reactive Behavioural agents	Dynamic spatial engine, Model libraries/plugins & tutorials available, Provision of policy settings for scenarios running ------------------------ Model writing in C++ and compiling into a DLLs, Envision's SDK provides high-level C++ wrappers ------------------------ Graphical user interface for intuitive model visualisation	Microsoft.NET Compiler -------------------- 32-bit and 64-bit Windows platforms -------------------- Desktop computer	Moderate	Medium-scale	Multi-paradigm GIS (Geographic Information System) based tool for analysing scenario-based coupled natural/human resource systems and community/regional integrated planning and environmental assessments
Eve http://eve.almende.com/ --------------------- Open source, Free	Java	Agents/ objects implemented as Java classes	Eve-API and library support for protocols (JSON-RPC) over the transport layers (HTTP, XMPP) ------------------------ Java ------------------------ IDE: Eclipse (managed by Maven's central repository)	On Windows, Linux, Unix, Mac OS X as servlets (i.e., standalone applications on Google App Engine, Amazon Webservices and in-browser via Javascripts), On mobile devices (e.g. Android) -------------------- Desktop computer, Workstation	Moderate	Small-scale ~ Medium-scale	General multi-purpose modelling and simulations

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3. Scope of agent-based modelling and simulation paradigm

One of the most fundamental properties of an ABMS tool is its scope; namely, the domain in which it is potentially able to execute modelling and simulation scenarios. In the next section, this article discusses the application areas and computing platforms currently in use for the implementation of ABMS from the viewpoint of assessing the modelling capacity or scalability of a simulation model.

3.1. Application domains of ABMS

ABMS is increasingly recognized in scientific disciplines such as ecology, climate change, economics, biology, agriculture,

Table 1 (*continued*)

ExtendSim http://www.extendsim.com/ --------------------- Closed source (block components are extensible & open source), Proprietary commercial software licenses (Single User, Floating or Concurrent User, Analysis RunTime, ASP: Application Service Provider, Student, Network)	ExtendSim's ModL language	Object-oriented agents or entities interacting via discrete-events	Models library available ------------------------ ModL programming and other external languages interfaced with ExtendSim ------------------------ User-friendly interactive graphical environment for visual model development	Windows XP, Vista, 7, 8, 10, or 2000 Mac OS X 10.4-6 -------------------- Desktop computer, Workstation	Moderate	Small-scale ~ Medium-scale	2D/3D simulations in a variety of fields (business, industry, healthcare, meteorology, air-defence, and academic)
FLAME (Flexible Large-scale Agent-based Modeling Environment) http://flame.ac.uk/ --------------------- Open source, GNU Lesser General Public License, Free	C	Agents as objects characterized by states (conditions), functions, and sets of variables	Sample libraries & tutorials available ------------------------ Graphical user interface, visualiser and validation tools	GNU C compiler (GCC), Xparser, libmboard (binary available for Windows), Graphviz (for viewing model state graphs) -------------------- Windows, Linux, Mac OS X -------------------- Laptop, Workstation, HPC supercomputers	Moderate	Large-scale	General multi-purpose simulations (cellular automata, economics, biology, medical, traffic situations, etc.)
FLAME GPU (Flexible Large Scale Agent Modelling Environment for the Graphics Processing Unit) http://www.flamegpu.com/ --------------------- Open source, FLAME GPU License Agreement, Free	C for CUDA ----------------- OpenGL	Reactive processing agents as communicating X-Machines with inputs and outputs	C/CUDA libraries available ------------------------ C-based scripting and optimized CUDA code	CUDA-4.1 SDK and compatible driver -------------------- Windows, Linux, Mac OS X -------------------- Laptop, Workstation, HPC supercomputers	Complex/Hard	High/ Large-scale	3D simulations for emergent complex behaviours in biology/medical domains (tissue cultures and signaling pathways) with multi-massive amounts of agents on GPU (Graphics Processing Unit)
FlexSim http://www.flexsim.com/ --------------------- Closed source, Proprietary, Trial version available	Microsoft.NET Framework ----------------- OpenGL	Agents/ objects implemented as C++ classes	FlexSim's library of standard customizable objects available ------------------------ Drag and drop model building, intuitive controls and dynamically display of output statistics as charts and graphs to	Microsoft.NET Compiler (required) Visual C++4 (optional) -------------------- Windows -------------------- Laptop, Graphics Workstation	Simple/Easy	Small-scale ~ Medium-scale	2D/3D simulations for manufacturing, production, distribution of logistics, supply chains, transportation, oil field or mining process, networking data flow, healthcare, optimization (with OptQuest plugin)
Framsticks http://www.framsticks.com/ --------------------- License depends on the module: GPL (JAVA GUI Client), LGPL (Framsticks GDK), Proprietary (Framsticks Theater Application)	Java ----------------- OpenGL	Evolutionary agents	FramScript (similar to JavaScript, C, C++, PHP) -------------------- Visual GUI (Framclipse IDE) for simulation and model development	Java Runtime Environment -------------------- Windows, Linux, Mac OS X -------------------- Desktop computer, Workstation	Simple/Easy	Light-weight/ Small-scale	2D/3D simulations of evolving agent-based systems and artificial life for research and education

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sociology, social sciences and many other disciplines of STEM (Science, Technology, Engineering and Mathematics) in simulating dynamic large-scale complicated systems and observing emergent behaviours [19,32,33]. Complex systems can be thought of simply as sets of interacting agents or entities. Agents may manifest organisms, humans, businesses, institutions, and any other entity that intends to pursue a certain goal. Agent-based models are particularly applied in the case of modelling complex phenomena, where a lot of agents or active entities interact among each other with certain inherent attributes to establish agency relationships, thereby facilitating automated reasoning and problem-solving [34,35].

Fundamentally, ABMS tools provide support to researchers and practitioners in investigating how the macroscopic behaviour of a system is dependent on the micro-level properties, constraints and rules Agents as objects are typified by specific states and sets of functional attributes, properties, or rules; in short 'behaviours' which may trigger special actions through the predefined parameters. Agent-supported simulation modelling

Table 1 (*continued*)

GAMA http://gama-platform.org/ --------------------- Open source, GNU GPLv2, Free	YourKit Java Profiler (OSGI plugin framework and Java annotations) ----------------- OpenGL	Reactive Behavioural agents	GAML modelling language for agent specification, Extensible libraries for agents architecture designing, Statistical and spatial analysis functions ------------------------ IDE: Eclipse platform based user interfaces with convenient plotting and graphical editors	Java Runtime Environment -------------------- Mac OS X, Windows, Linux -------------------- Desktop computer, Graphics Workstation	Moderate	Medium-scale ~ Large-scale	2D/3D modelling & development platform for building spatially explicit agent-based simulations (arbitrary complex GIS data as the bases of agents), land-use and land-planning, social, institutional, economical, ecological or biophysical systems
GALATEA (Glider with Autonomous, Logic-based Agents, TEmporal reasoning and Abduction) http://galatea.sourceforge.net/QuickStartGuide.htm http://galatea.sourceforge.net/Home.htm --------------------- Open source, Free	Java	Logic-based agents or objects (as observe-reason-act processes)	GALATEA's libraries/ packages, toolkits, kernel (DEVS based simulation engine for discrete- events), HLA framework, demos and documentation are available from sourceforge repository ------------------------ Java ------------------------ IDE: Eclipse/Apache-Ant	Java Development Kit -------------------- Linux, Unix, Windows -------------------- Desktop Computer	Moderate	Medium-scale	Modelling and simulation of discrete-event simulation, continuous, combined and multi-agent systems (e.g., hardware and software co-design, communication systems, manufacturing systems, biology, sociology, economics)
GridABM http://gridabm.sourceforge.net/ --------------------- Open source, GPL, Free	Java (GridABM is based on Java, RePast, and ProActive)	Reactive, BDI agents	ProActive Java library for deploying objects on different remote computers ------------------------ Java ------------------------ IDE: Eclipse	Java Runtime Environment -------------------- Linux, Windows -------------------- Multi-core computers, Computing clusters, Computational grids	Complex/Hard	High/ Large-scale	High-performance agent-based distributed cellular automation models based on Repast
GROWLab http://www.icr.ethz.ch/research/growlab --------------------- Open source, Free	Java	Agents/ objects implemented as Java classes	GROWLab's model library & API available ------------------------ Java ------------------------ IDE: Eclipse	Java Runtime Environment -------------------- Mac OS X, Windows, Linux -------------------- Desktop computer	Moderate	Small-scale ~ Medium-scale	Social phenomena
HLA_Agent (High Level Architecture Agent) http://www.agents.cs.nott.ac.uk/simulation/hla_agent -------------------- Open source, Free	C++	Reactive, Deliberative, Cognitive agents	C++	Linux, Unix -------------------- Workstation, Large-scale parallel/distributed computing clusters	Complex/Hard	High/ Large-scale	Complex adaptive systems, evolutionary computation, social & natural sciences, mapping passenger flow, manufacturing, military combat scenarios, high performance computing
HLA_RePast http://www.cs.bham.ac.uk/research/projects/hlarepast/ -------------------- Open source, Free	Java	Reactive/BDI object-oriented agents	Java	Linux, Unix -------------------- Workstation, Large-scale parallel/distributed computing clusters	Complex/Hard	High/ Large-scale	Cellular automata, complex adaptive systems, evolutionary computation, social & natural sciences, mapping passenger flow, manufacturing, military combat scenarios, high performance computing

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libraries and tools have now been in existence for many years assisting scientists and professionals in constructing such models [36]. The ultimate aim is to build simulations of complex systems that evolve as a set of interacting artefacts among the multiple decentralized modules. Individual objects or agents refer to the elements which live in the environment and have a set of properties that can change during the course of time. In a biological system, agents can manifest themselves as standalone distinct spatial objects like cells or molecules that may reside under a discrete or continuum setup [19]. In social systems, understanding a political or economic system requires more than an understanding of the individuals that comprise the system. It also requires understanding how the individuals interact with each other, and how the results can be more than the sum of parts [37].

The ABMS notion is well suited to the social science objectives and for studying systems or units that exhibit the two key

Table 1 (*continued*)

IDEA (Interactive Design Environment for Agent system) http://www.ka.riec.tohoku.ac.jp/idea/ Open source, Free	Java	Reactive, Proactive, Deliberative agents	External API-jars can be integrated with IDEA system Agents' production rule based knowledge & Java programs as associated baseprocesses IDEA's built-in integrated development environment	Java Runtime Environment Mac OS X, Windows, Linux, Unix Desktop computer	Moderate	Medium-scale	Applied sciences (knowledge based systems, multimedia, micro-grid operation, distributed network management, ubiquitous care-support or assisted services, information retrieval and so on)
Insight Maker http://insightmaker.com/ Open source, Free, GPLv3	JavaScript	Reactive Behavioural agents	Insight Maker API for adding interactivity to models JavaScript Graphical environment for model design, initialization, simulation	Java Virtual Machine enabled Internet browser is required Mac OS X, Windows, Linux Desktop computer	Moderate	Small-scale ~ Medium-scale	Differential equation or dynamical systems modelling, such as spatially-aware model of infectious disease spread
JAMEL (Java Agent-based Macro-Economic Laboratory) http://p.seppecher.free.fr/jamel/ Open source, GPL, Freeware	Java	Reactive agents	Free library JFreeChart API for the dynamic presentation of economics data Java IDE: Eclipse	Any Java-enabled platform (Java 1.6 or higher) Runs as an applet in a Web-browser Desktop computer	Simple/Easy	Light-weight/ Small-scale	Building agent-based macroeconomic simulations
JAMSIM (JAva MicroSIMulation) https://github.com/compassresearchcentre/jamsim Open source, Freeware	Java R statistical programming language for outputs	Agents composed as a `scapes' hierarchy or collection of agents that represents basic building blocks (such as an offspring, parent, or household unit etc.)	Casper (data set manipulation library) & Colt (a set of open source Java libraries for high performance scientific/technical computing) Model implementation in Java. R has been used for output generation and graphical output Ascape Swing GUI	Java Runtime Environment Mac OS X, Windows, Linux Desktop computer, Workstation	Moderate	Medium-scale	Dynamic discrete-time policy-oriented microsimulation government projects (taxation/pensions)
Janus http://www.janus-project.org/Home Open source, GPLv3 for non-commercial use, or JIUL/ JCRL usage/redistribution commercial license, Free	Java	Recursive holon agent (composed of a set of structures) + Various agents as extra-modules: Jaak (Reactive), Belief-Desire-Intention (BDI), FIPA-ACL	Agent behaviours supported scripting languages: Groovy, Javascript, JRuby/Ruby, Jython/Python Lisp, Lua scripting language IDE: Maven/ Eclipse	Java Runtime Environment (Java 1.6 or higher) Windows, Mac OS X, Unix, Linux, Android, Web Desktop computer	Moderate	Medium-scale	General purpose platform with organizational and holonic agent-based simulation layers
JAS (Java Agent-based Simulations) http://jaslibrary.sourceforge.net/ Open source, GNU LGPL (associated third party licenses: usually non-proprietary), Free	Java	Agents/ objects implemented as Java classes	A collection of built-in open source libraries to create and share models Java IDE: Eclipse	Any Java-enabled platform (Java 1.5 or higher) Desktop computer	Simple/Easy	Medium-scale	Simulations of dynamic social systems, genetic algorithms and neural networks

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properties: (1) the system is constituted by the interacting active entities or agents for negotiation and conflict resolution; (2) the system orchestrates gradual emerging patterns, that is, attributes prevailing from the dynamic interactions of agents that may not be inferred merely by aggregating the inbuilt characteristics of agents. Therefore, it can be categorically stated: "when interactions of the agents are contingent on past experience, and especially when the agents continually adapt to that experience, mathematical analysis is typically very limited in its ability to derive the dynamic consequences". In such cases, agent-based modelling often offers the only practical method of analysis [38].

Furthermore, agent-based modelling can equally be interpolated to offer pragmatic solutions to many problems important to our environment, wildlife, healthcare and finance domains. In addition, these models have long been applied to epidemiological

Table 1 (*continued*)

JASA (Java Auction Simulator API) http://jasa.sourceforge.net/ --------------------- Open source, GPLv2, Free	Java	Adaptive Trading agents	Third-party libraries (ECJ, RePast, Commons Collections, Apache Commons Mathematics, GNU Trove) ------------------------ Java ------------------------ IDE: Eclipse/Apache-Ant	Any Java-enabled platform -------------------- Desktop computer	Moderate	Medium-scale	Simulations of computational economics
JAS-mine (Java Agent-based Simulation library - Modelling In a Networked Environment) http://www.jas-mine.net/ --------------------- Open source, Free	Java	Agents/ objects implemented as Java classes	JAS-mine built-in libraries available ------------------------ Java ------------------------ IDE: Eclipse	Any Java-enabled platform -------------------- Desktop computer	Moderate	Medium-scale	Simulations of data-driven models, discrete-event/continuous simulation, dynamic microsimulations of specific processes (aging, educational choices, labor market events, household formation, etc.), statistical analysis
JCASim (Java-based Cellular Automata Simulation) http://www.jcasim.de/ -------------------- Closed source, Free	Java	Interacting Reactive agents	An applet for HTML presentations ------------------------ A stand-alone interactive application or simulator editor in Java, and Cellular Description Language [CDL] for input to simulation which translates automatically into Java	Any Java-enabled platform -------------------- Runs as an applet in a Web-browser -------------------- Desktop computer	Simple/Easy	Light-weight/ Small-scale	Microscopic cellular automata simulated in different lattices 1D/2D/3D
jES (Java Enterprise Simulator) http://terna.to.it/jes/ -------------------- Open source, Free for academic purposes	Java	Objects or decision nodes based on independent piece of code or action rules and algorithms to represent agents as avatars of actual people	A stand-alone interactive application or simulator editor based on Java	Any Java-enabled platform -------------------- Desktop computer	Simple/Easy	Light-weight/ Small-scale	Simulations in the context of enterprise behaviour and activities
LSD (Laboratory for Simulation Development) http://www.labsimdev.org/Joomla_1-3/ -------------------- Open source, GPL, Free	C++ source code, Tcl/Tk GUI toolkit, Gnuplot graphical package	Agents/ objects implemented as C++ classes	A collection of built-in open source libraries to create and share models ------------------------ C++, LSD language in Eclipse-CDT ------------------------ User-friendly model development editor	GNU C++ compiler -------------------- Windows, Unix, X11, Mac OS X, Linux -------------------- Desktop computer, Workstation	Moderate	High/ Large-scale	Economic and social science simulations; Can generate multiple formats for graphs: time series, cross-section, 2D and 3D scatter plots, frequency histograms

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problems thereby contributing towards the welfare of humanity. ABMS can reproduce many characteristics of real outbreaks of diseases and the predictions are easy to comprehend, with disease control managers being accepting of the simulation results and thereafter successfully intervening with pre-emptive vaccination strategies [39]. Latterly agent-based simulation has become a notable technique in the modelling and analysis of electricity supplies. Quite a lot of biological applications of ABMS have artificial life as their focal point [7]. Some studies are directed towards exploring the physiology of cells, organisms' micro-structures and internal organs. Within the medical domain, ABMS has focused on human ailments, acute inflammation, cancerous malignant tumours, wound healing, epidemiology and infection, immunology, vascular system and signalling/metabolic processes.

A variety of other application areas of ABMS in engineering and sciences exists including: design of self-organizing systems either continuous or discrete-event, simulating fluid flow-rates, immunology, path-signalling genetics/molecular networks, physiological fluctuations including the systems' ability to react to a trail of environmental impulses/stimuli, pollutants analysis to formulate policy rules for greener habitat, transportation and logistics, failures detection and diagnosis in distributed systems, manufacturing, production, design of safety critical systems, and so on. Further utilization and uptake of ABMS is anticipated in social micro-simulation and optimization problems, like crowd pattern sensing, traffic flow and urban supply chains. Scientists and engineers are investigating the use of ABMS in the computational science, particularly in terms of systems biology [19]. An effective incorporation of ABMS pilot-cases for improving the resilience of aircraft runway operations is reported in [40]. A precise review of ABMS for the effective land use has been conducted in [41], thereby pinpointing the decision-making characteristics (e.g. interactions, uncertainty, heterogeneities, learning, adaptation) of agents.

Agent-based models have established their worth within business, finance, operational innovation and management related research organizations. Management educators and scientists are

Table 1 (*continued*)

MACSimJX http://www.agentcontrol.co.uk/ -------------------- Closed source, Free	C++ (also includes a wrapper to enable interaction with Java programs)	JADE's (Java Agent DEvelopment) Framework, and FIPA-compliant agent classes	API for MACSimJX available ------------------------ C/C++ or Java ------------------------ IDE: Eclipse/ Maven	Any Java-enabled platform for JADE 3.6.1 & MATLAB-Simulink 2009/2010 -------------------- Desktop computer	Moderate	Medium-scale	Modelling and simulation environment integrated with Matlab-Simulink (for developing dynamic, embedded, decentralised control systems, e.g. aircraft Boeing 747 sensor unit's flight dynamics and kinematics undergoing a complex series of manoeuvres) using JADE (an environment for developing agents)
MASON (Multi-Agent Simulator Of Neighborhoods or Networks) http://cs.gmu.edu/~eclab/projects/mason/ -------------------- Open source, Academic Free License version 3.0	Java.net	Agents/ objects implemented as Java classes	Optional suite of libraries available to develop models, generate movies, charts/graphs, and to recompile MASON ------------------------ Java ------------------------ IDE: Eclipse or NetBeans	Any Java-enabled platform (Java 1.3 or higher) -------------------- Windows, Unix, X11, Mac OS X, Linux For 3D MASON: Sun's Java3D, Windows user's OpenGL version of MASON -------------------- Desktop computer, Workstation	Complex/Hard	Medium-scale ~ High/ Large-scale	General multi-purpose 2D/3D simulations (social complexity, physical and abstract modelling, artificial intelligence, robotics, and machine learning)
MASS (Multi-Agent Simulation Suite) http://www.aitia.ai/en/web/iaws/mass -------------------- Proprietary, Free version available	Java	Agents/ objects implemented as Java classes	Models library available ------------------------ FABLES (Functional Agent-Based LanguagE for Simulations); Java; and possibly running Repast and NetLogo simulations ------------------------ FABLES integrated modelling environment with user-friendly wizards and GUIs for writing models, generating visualisations of simulation data	Java Runtime Environment (Java 1.5 or higher) -------------------- Windows, Mac OS X, Linux -------------------- Desktop computer, Workstation	Moderate	High/ Large-scale	General purpose distributed simulations (complex social economic system, traffic situations)
MASyV (Multi-Agent System Visualization) http://masyv.sourceforge.net/ -------------------- Open source, Free	C	Agents/ objects implemented as C class constructs	A set of functions libraries available ------------------------ Client simulations in C language ------------------------ Graphical User Interface (GUI) for the visual representation of client simulations	GCC (GNU C compiler), OpenGL compatible graphics library (e.g. Mesa), GTK runtime support GtkGLExt available -------------------- Client/server Unix version, Linux, Mac OS X, X11 -------------------- Desktop computer, Workstation	Complex/Hard	Medium-scale	2D/3D visualisations of cellular automata

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always in search of the novel and compelling methods of imparting the courses' main ideas to the pupils. While agent-based models alone often are not sufficient to explain the intricate details of a selected topic, these serve as a supplement to conventional lecturing approaches. Agent-based modelling/simulation offers an effective way of disseminating management concepts using an inherently visual medium. Agents may model firms, people within institutions, or spanning application processes in industry. With the help of agent-based modelling, users define interactions between the objects/agents in their domain of interest, and then using these model to generate their own real-world system models [34]. An Integrated Development Environment (IDE) is a standalone application programming environment that is populated with a typical code editor, compiler, tester/debugger and visualiser or interactive Graphical User Interface (GUI) builder. What makes this methodology interesting to a student is that the models are intuitively visualised on esthetically appealing user interfaces; more specifically, the cases where the micro-level trends of individuals have subsequent direct impacts on the universal/macro-scale properties of the entire unit. Therefore, audience can observe the dynamical interactions between agents and the consequents on each individual agent and henceforth impact on the overall system performance [34].

Table 1 (*continued*)

Mathmatica® (Wolfram) http://www.wolfram.com/solutions/industry/social-sciences/ -------------------- Closed source, Proprietary, Trial version available	Wolfram Language, C/C++, Java and Mathematica	Agents/ objects implemented as class constructs	Standard APIs and a set of functions libraries available ------------------------ Wolfram multi-paradigm programming language and its interface with C/C++/Java, and Mathematica-specific symbolic computation algorithms ------------------------ Built-in code editor and debugger and full Eclipse-based IDE	Linux, Windows, Mac OS X -------------------- Desktop computer, Workstation	Moderate	Medium-scale	Simulation of social and behavioural sciences, customer movements in a store, complex adaptive social systems or artificial societies
MATSim (Multi-Agent Transport Simulation toolkit) http://matsim.org/ -------------------- Open source, GPL, Free	Java	Agents/ objects implemented as Java classes	Java ------------------------ IDE: Eclipse/Maven	Any Java-enabled platform (Java Standard Edition SE-6) -------------------- Desktop computer, Workstation, Large-scale scientific computing clusters	Complex/Hard	Extreme-scale	Simulations of transport mobility systems and Geographical Information Systems (GIS) based evacuation scenarios
Mesa https://pypi.python.org/pypi/Mesa/ https://github.com/projectmesa/mesa/ -------------------- Open source, License: Apache 2.0, Free	Python	Agents as class constructs (having a unique identifier consisting of variable and action)	Python ------------------------ Visualisations in a browser window, using JavaScript; Result analysis using Python's data interpretation tools	Python virtual environment (virtualenv) -------------------- Desktop computer	Moderate	Light-weight / Small-scale ~ Medium-scale	General purpose artificial life related simulations (Basically, Mesa is a Python 3 based alternative to NetLogo, Repast, or MASON)
Mimosa http://mimosa.sourceforge.net -------------------- LGPLv2 license and CIRAD copyright, Free	Java	Agents/ objects implemented as Java classes	Conceptual and concrete editors for visual modelling + Behaviour specification of entities in Eclipse IDE with Java/Jess/Python /Prolog/Smalltalk /Scheme (functional programming language)	Any Java-enabled platform (Java 1.5 or higher) -------------------- Desktop computer, Workstation	Moderate	Medium-scale	Building conceptual models for running the economic, ecological, social simulations
MIMOSE (MIcro and Multilevel MOdelling SoftwarE) http://userpages.uni-koblenz.de/~moeh/projekte/mimose.html -------------------- Closed source, GPL, Free	Java	Agents/ objects implemented as Java classes	A model description language (a derivative of functional coding paradigms) ------------------------ Graphical user interface for model design, initialization and simulation	Client/server Sun/Solaris version, X11R5/6, Linux, Java based client on Windows NT, Linux, Solaris -------------------- Desktop computer	Moderate	Medium-scale	Simulations in social sciences, epidemiology, education/research
MOBIDYC (MOdelization Based on Individuals for the DYnamics of Communities) http://w3.avignon.inra.fr/mobidyc/index.php/English_summary -------------------- Open source, GPL, Free	Smalltalk in VisualWorks (Cincom Systems)	Agents/ objects implemented as class constructs	Smalltalk ------------------------ Template-based graphical user interface	VisualWorks from Cincom Systems, and Java 1.4.2 or higher for Math scripts -------------------- Mac OS X, Windows XP, Unix-Solaris, Linux -------------------- Desktop computer	Simple/Easy	Light-weight/ Small-scale	Academic simulations in ecology, cellular automata, biology, and environment

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3.2. Implementation platforms for ABMS

Software agent-directed simulation and modelling can be undertaken on various devices; tiny notebooks to desktops, large-scale workstations or powerful compute clusters and supercomputers. In addition to this, ABMS can be realised using general purpose computer programming languages, as well as specially designed toolkits and commercially available dedicated software that addresses some specific essentials for modelling the simulation agents [42]. Typically, the simulations of agent-based models (ABM) entails dealing with huge amount of agents (in millions) cannot be modelled within a single computer node due to memory issues. This implies the need for a specialized workstation or high performance parallel programming platform. Therefore, it is often necessary to run distributed simulations using a dedicated

Table 1 (*continued*)

Mobility Testbed https://github.com/agents4its/mobilitytestbed -------------------- Open source, GPL, Free	Java	Agents/ objects implemented as class constructs	Benchmarking scenarios available ------------------------ Java ------------------------ IDE: Eclipse	Windows, Mac OS X, Linux, Unix -------------------- Desktop computer	Moderate	Medium-scale	Simulations for transportation (networks, activities, life-cycles) and mobility (multi-modal route and journey planning) services
Modgen (Model generator) http://www.statcan.gc.ca/eng/microsimulation/modgen/modgen -------------------- Closed source, Free	Microsoft Visual Studio	Agents/ objects implemented as linked actors having specific characteristics as states/events	Model libraries available ------------------------ C++, Modgen language ------------------------ Modgen's generic visual interface for editing parameters, setting execution control options, running the model and browsing the outputs, Standalone BioBrowser for modelling/visualisation	Standard Edition of Microsoft Visual Studio's C++ environment -------------------- Microsoft Windows -------------------- Desktop computer, Workstation	Moderate	Medium-scale	Dynamic social science microsimulations for the socio-economic and demographic development of societies
NetLogo http://ccl.northwestern.edu/netlogo/ -------------------- Open source, GPL, Free	Scala code compilation to Java byte-code (fully interoperable with Java and other JVM codes) ----------------- For 3D graphical visualisation, NetLogo uses a Java JOGL API for OpenGL rendering	Active objects with simple goals implemented as mobile agents (turtles, patches, links, and the observer)	Models library available ------------------------ NetLogo language	Any Java Virtual Machine with version 5 or later -------------------- Any platform: Windows 7, Vista, 2000, and XP, Mac OS X, Linux, Unix -------------------- Desktop computer	Simple/Easy	Medium-scale ~ Large-scale	2D/3D simulations in social and natural sciences, teaching/research
OBEUS (Object Based Environment for Urban Simulation) http://www.tau.ac.il/~bennya/1OBEUS.html ------------------- Closed source, Free	Microsoft.NET Framework	Agents/ objects implemented as C++ classes	Microsoft.NET languages (C#, C++, Visual Basic)	Microsoft.Net Compiler -------------------- Windows -------------------- Desktop computer	Moderate	Medium-scale	Simulations of Geographic Automata System (GAS) or urban or regional planning areas
Pandora http://xrubio.github.io/pandora/ ------------------- Closed source, Free	Microsoft.NET Framework	Agents/ objects implemented as C++/Python classes	Python (for fast prototyping) or C++ (for complex models) ------------------------ Cassandra GUI tool for results analysis with 2D/3D visualisations	Microsoft.Net Compiler -------------------- Windows -------------------- High-Performance Computers, Clusters and PCs using MPI/OpenMP	Moderate	High/ Large-scale	High-performance computing environments, Geographical Information System (GIS) support, social and environmental phenomena, archaeology
PDES-MAS http://www.cs.bham.ac.uk/research/projects/pdesmas/ -------------------- Open source, Free	C++	Situated agents as MPI-based Agent Logical Processes (ALPs) implemented as C++ classes	C++	Linux, Unix -------------------- Workstation, Large-scale parallel/distributed computing clusters	Complex/Hard	Extreme-scale	Complex adaptive systems, social & natural sciences, mapping passenger flow, manufacturing, military combat scenarios, high performance computing

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computing cluster or a grid to reduce the simulation time. To harness the full potential of ABMS paradigm, the research scientists are keenly looking into a next-generation agent-based simulation testbeds that can be scale-up to the exascale computing structures, to attain indelible footprints in the multi-dimensional disciplines of science and engineering [42–47].

As we have argued, the practical applications of ABMS may be categorized as the highly elegant ones, simplistic academic research prototypes, and extreme-scale automation supported stringent systems. Maximalist models embed all possible manifestations of the system, whereas minimalist designs are founded on a set of classic pre-assumptions that merely encapsulate the most remarkable system's facets. Hence, the exploratory agent-based models are tested under a number of suppositions that can be varied over a vast multitude of experimental simulations. For instance, Argonne National Laboratory USA, have successfully executed exascale ABMS models on the IBM BlueGene with the financial support from 'SciDAC

Table 1 (*continued*)

PedSim (Pedestrian crowd Simulation) http://pedsim.silmaril.org/ ------------------- Open source, GPL, Commercial license also available, Free	C++	Agents/ objects implemented as C++ classes	PEDSIM library of routines available for incorporating in user's own code ------------------------ C++ ------------------------ Graphical user interface for intuitive model visualisation	Microsoft.Net Compiler -------------------- Linux, Windows, Mac OS X -------------------- Desktop computer	Simple/Easy	Light-weight/ Small-scale	Simulation system and library for microscopic pedestrian crowd mapping
PS-I (Political Science-Identity) http://ps-i.sourceforge.net/ ------------------- Open source, GPLv2, Free	C	Agents/ objects implemented as class constructs	Models library available ------------------------ Declarative model specification language; TCL/TK scripts to apply graphic effects ------------------------ User-friendly graphical interface	GNU C compiler (GCC), Cross platform binaries available for Windows and Linux; Unavailable for Macintosh users, however emulation possibility is there for Windows, NT, or Linux environment -------------------- Desktop computer	Simple/Easy	Light-weight/ Small-scale	Simulations of political phenomena, cultural, psychological, administrative, geographical, and other social factors
Repast-J or Repast-3 (REcursive Porus Agent Simulation Toolkit) http://repast.sourceforge.net/repast_3/index.html ------------------- Open source, BSD, Free	Java/C#	Reactive/BDI object-oriented agents	Agent-templates + models library of built-in routines available ------------------------ Java; C#; Managed C++/Lisp/Prolog; Visual Basic.Net; Python scripting ------------------------ Built-in simulation results logging facility and graphing tools to display output ------------------------ IDE: Eclipse ------------------------ User-friendly graphical interface	Repast J: Java Runtime Environment (Java 1.4 or higher) Repast.Net: Microsoft.Net Compiler -------------------- Windows, Mac OS X, Linux -------------------- Desktop and vast-scale scientific computing clusters	Complex/Hard	High/ Large-scale	Simulations of social networks and integrated support for Geographical Information Systems (GIS), genetic algorithms
Repast HPC https://repast.github.io/repast_hpc.html -------------------- Open source, BSD, Free	C++ using MPI for parallel Operations + Boost C++ portable source libraries	Reactive/BDI object-oriented agents	Standard or Logo-style C++ ------------------------ IDE: Eclipse	Windows, Mac OS X, Linux, Unix -------------------- Large-scale distributed clusters and HP supercomputers	Moderate ~ Complex/Hard	Extreme-scale	Simulations in computational social sciences, cellular automata, complex adaptive systems
Repast Simphony (Repast-S) https://repast.github.io/repast_simphony.html -------------------- Open source, BSD, Free	Java	Reactive/BDI object-oriented agents	Agent-templates + models library of built-in routines available ------------------------ Java; Groovy (~easier Java); ReLogo (~Repast's NetLogo-like language) ------------------------ IDE: Eclipse ------------------------ User-friendly graphical interface with flowcharts option for visual intuitive model development and visualisation	Java OpenGL (JOGL) - a wrapper library that allows OpenGL + Sun's Java3D JDK-framework -------------------- Windows, Mac OS X, Linux -------------------- Workstation, Small computing clusters	Complex/ Hard yet Flexible	High/ Large-scale	2D/3D simulations in social sciences, consumer products, supply chains, Geographical Information Systems (GIS), cellular automata, complex adaptive systems, etc.

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Programme' [48]. Other efforts have explored the utilisation of Grid computing for Agent-based simulation [49]. Clearly, ABMS research must be advanced along multi-lines prior to show-casing it as a viable approach to take into account the needs of emerging cloud and extreme-computing paradigms. This eventually could be relied upon to make decisions in a tangled and ever changing world [19].

4. ABMS software's evaluation & discussion

In this survey, a meticulous effort has been undertaken by delving deep into each individual ABMS tool in order to expose notable features from the reference guides, users' manuals and documentation. Where deficiencies existed in the tools' technical descriptions, archive files were downloaded and extracted to

Table 1 (*continued*)

Scratch https://scratch.mit.edu/ -------------------- Closed source, GPLv2, CC-BY-SA 2.0 license, Free	Squeak (an open-source programming environment based on Smalltalk)	Sprites or objects encapsulating state (variables) and behaviour (scripts)	Projects-startup libraries available ------------------------ Programming scripts made by snapping graphical chunks/blocks in the form of stacks ------------------------ Interactive visual programming interface	Scratch 2: Web browser & Adobe Flash Player, Scratch 1.4: Windows 2000 or later, Mac OS X 10.4 or later, Ubuntu Linux 9.04 or later, Scratch 2 Offline Editor: Mac (Adobe Air 20), Windows, and some versions of Linux (32 bit) -------------------- Desktop computer	Simple/Easy	Light-weight/ Small-scale	Self-directed creative learning software for students and educators to make 2D/3D animated games in social sciences, geography, mathematics, linguistics, arts, computer science
SEAS (System Effectiveness Analysis Simulation) http://teamseas.com/ -------------------- EULA, Free with government approval	C++	Agents/ objects implemented as C++ classes	Tactical Programming Language (TPL)	Windows -------------------- Desktop computer, Workstation	Moderate	Light-weight/ Small-scale	2D/3D simulations of complex adaptive systems, military war-fighting scenarios
SeSAm (Shell for Simulated Agent Systems) http://www.simsesam.de/ -------------------- Open source, LGPL, Free	Java	Agents/ objects implemented as Java classes	Visual modelling language	Windows; Linux, Mac OS X -------------------- Desktop computer	Simple/Easy	High/ Large-scale	Simulations in social sciences (logistics, production, traffic, passenger flow, healthcare, biology, urban planning), research/teaching
SimAgent http://www.cs.bham.ac.uk/research/projects/poplog/packages/simagent.html -------------------- Open source, Free, MIT/XFREE86 license for poplog libraries	Poplog	Reactive, Deliberative, Cognitive agents	Robust extensible multi-purpose coding format 'Pop-11' which supports programming in Prolog, Common Lisp or Standard ML	Windows, Mac OS X, Linux, Unix -------------------- Desktop computer, Workstation	Complex/Hard	High/ Large-scale	Simulations in research/education, social sciences (biology, psychology), evolutionary computation
SimBioSys http://www.lucifer.com/~david/SimBioSys/ -------------------- Artistic license agreement, Free	C++	Agents/ objects implemented as C++ classes	Class-libraries available ------------------------ C++ ------------------------ IDE: Eclipse-CDT	Microsoft.Net or GNU C++ compilers -------------------- Any platform that supports C++ -------------------- Desktop computer	Moderate	Medium-scale	Evolutionary simulations in biological and social sciences
SimEvents (MATLAB®) http://uk.mathworks.com/solutions/discrete-event-simulation/index.html?s_tid=gn_loc_drop -------------------- Closed Source, Proprietary commercial software (Standard/Education/ Home/Student versions on-purchase licenses), Trial version available	C, C++, Java, MATLAB code language	Collection of independent object-oriented agents/ entities interacting via discrete-events	SimEvents® (together with MATLAB®, Simulink® and Stateflow® functions libraries, toolboxes, and add-ons) -------------------- MATLAB® coding syntax -------------------- Built-in graphical programming environment	Windows, Linux, Mac OS X -------------------- Desktop computer, Workstation	Moderate	Medium-scale ~ Large-scale	Simulations to optimize supply chain processes for manufacturing and operations, forecasting, capacity planning aerospace, automotive, mission plans
Simio http://www.simio.com/products/ -------------------- Closed Source, Proprietary commercial software (Design/Team/ Enterprise/Academic versions available on-purchase licenses), Free Personal Edition available	C#	Agents as objects characterized by properties, states and behaviours	Standard object libraries available -------------------- Data import/export as xlsx or csv files -------------------- Built-in graphical programming environment	Windows -------------------- Desktop computer, Workstation	Moderate	Medium-scale ~ Large-scale	2D/3D simulations in advanced predictive analysis, tourist flow, manufacturing, military solutions, production, scheduling, transportation, logistics, supply chain, mining industry, healthcare, maritime/ports, airfreight services, optimization (with OptQuest plugin)

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examine the source code and the compiler used to develop custom plugins. Furthermore, several tools' executables were installed for running the tutorial samples so as to ascertain the availability of models' libraries, add-ons and APIs, and to accurately identify the programming language and agents' types that are required for the model design and implementation. Even so, any rare discrepancy in the tool's reported features and functionality should be contributed to subjective differences and unintentional human errors or omissions such as our insufficient comprehension on some aspects of these ABMS software. Hence, a recommendation for the readers would be to investigate the ABMS tools further for greater in-depth analysis in line with their specific demands.

Table 1 (*continued*)

SimJr http://code.google.com/p/simjr/ -------------------- Open source, BSD, Free	Java	Cognitive agents	JavaScript ------------------------ IDE: Eclipse	Java Runtime Environment -------------------- Windows, Linux, Mac OS X -------------------- Desktop computer	Simple/Easy	Light-weight/ Small-scale	Simulations of air and ground forces, military scenarios, different aspects of human behaviours or actions modelling, command and control modules, intelligence analysis, and information visualisation
SimSketch http://modeldrawing.eu/ -------------------- Closed source, Free	Java	Reactive Behavioural agents	Java Web Start (JavaWS)	To run simulations: a Java (Java 6 or higher) enabled Internet browser is required -------------------- Windows, Linux, Mac OS X -------------------- Desktop computer	Simple/Easy	Light-weight/ Small-scale	Educational relevant scientific phenomena for young learners
Simul8 http://www.simul8.com/ -------------------- Closed source, Proprietary commercial software licenses (Basic/Professional-3D/ Team/Education) versions, Concurrent user license (Network) edition	Visual Logic Code	Agents as physical, logical or activity-based objects	Sample templates and libraries of interactive models available ------------------------ Coding: Visual Logic ------------------------ Data import/export as xlsx, csv, txt, rtf files or to V.I.S.A ------------------------ Intuitive drag & drop interface	Windows NT, 95, 98, 2000, XP, Vista, 7, 8, 10. For Mac OS X, use virtualization software like VMware Fusion or Parallels -------------------- Desktop computer, Workstation	Moderate	Medium-scale ~ Large-scale	2D/3D simulations in education, healthcare, manufacturing, logistics, contact centre or client–based services, supply chains, capacity planning, administrative workflows, optimization (with OptQuest plugin)
SOARS (Spot Oriented Agent Role Simulator) http://www.soars.jp/en -------------------- Open source, Free	Java	Role-based agents	JavaScript ------------------------ Visual programming interface	Java Runtime Environment -------------------- Windows, Linux, Mac OS X -------------------- Desktop computer	Simple/Easy	Light-weight/ Small-scale	Simulations of social, business, public health, and organizational systems, Geographic Information System (GIS), epidemiology
StarLogo http://education.mit.edu/starlogo/ -------------------- Closed source, Clearthought Software License Version 1.0, Free	Java/YoYo	Procedural agents having a range of potential functions	Template Wizard available for creating different types of active objects or turtles with simple goals ------------------------ StarLogo scripting – a graphical or visual programming language	Windows, Unix, Linux, Solaris, Mac OS X (With Java 1.4 installed) -------------------- Desktop computer	Simple/Easy	Light-weight/ Small-scale	Simulations in social and natural sciences, education, for depicting the behaviour of decentralized models (bird flocking, traffic jamming, and ant colony formations)
StarLogo TNG http://education.mit.edu/projects/starlogo-tng -------------------- Closed source, SLTNG License v1.0, Free	OpenGL programming	Procedural agents having a range of potential functions	StarLogo TNG block-based scripting – a graphical programming language	Windows, Mac OS X -------------------- Desktop computer	Simple/Easy	Light-weight/ Small-scale	3D simulations of educational models and video games
Sugarscape http://sugarscape.sourceforge.net/ -------------------- Open source, GPL, Free	Java	Agents/ objects implemented as Java classes	Java ------------------------ User-friendly environment for visual model development	Java Runtime Environment -------------------- Within any Java-enabled platform, runs as an applet in a Web-browser -------------------- Desktop computer	Simple/Easy	Light-weight/ Small-scale	Simulations in social sciences, cellular automata, education

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4.1. Comparison criteria

Overall, this review considers the significant features, merits, weaknesses and limitations of the surveyed agent-based modelling and simulation software tools. Evaluation criteria include:

- Source-code specification, online availability, distribution license / legibility as an open or closed source;
- Implementation types of agents primarily based on the interaction mechanism during simulation activity;
- Programming language requirements and provision of an Application Programming Interface (API) together with availability of built-in libraries for incorporation within the user's source-code for developing agent-based models;
- Availability of a graphical programming interface for code editing and simulation running, or intuitive visual programming user interface for the model rendering tasks;
- Identification of the compiler, operating system support, and platform/hardware requirements/constraints for the model

Table 1 (*continued*)

Swarm http://www.swarm.org/index.php/Swarm_main_page -------------------- Open source, GPL, Free	Java, Objective-C (an object-oriented extension of the C coding language)	Collection (swarms) of independent object-oriented agents interacting via discrete-events	Swarm models library of built-in routines available ------------------------ Objective-C; Swarm-code; Java ------------------------ IDE: Eclipse	Windows, Linux, Mac OS X, Solaris, IRIX, HPUX 9/10/11 --------------------- Personal computer, Workstation, Large-scale scientific computing clusters and HP supercomputers	Complex/Hard	Extreme-scale	Simulations of complex adaptive systems in social or biological sciences; supply chain optimization and logistics; consumer behaviour with social network effects; distributed computing; workforce/traffic /portfolio management
TerraME http://www.terrame.org/doku.php -------------------- Open source, Free	C++/Lua	Agents/ objects implemented as C++/Lua scripts' classes	TerraME's modelling models libraries & API (based on C++ and an extension of the "Lua" programming language) are available ------------------------ IDE: Eclipse + Interactive GUI (Graphical User Interface) for model running	Windows, Macintosh, Linux (tested on Ubuntu 12.04) --------------------- Desktop computer, Workstation	Moderate	Medium-scale	Multi-paradigm spatial dynamical systems, cellular automata, Geographical Information Systems (GIS), terrestrial systems, land-change/hydrologic/ species-dispersion/climate models
UrbanSim http://www.urbansim.org/ -------------------- Open source, GNU General Public License, Free	Opus with base language Python and Numpy as numerical library	Agents/ objects implemented as class constructs of Python-based custom domain-specific programming language "Tekoa"	Models library available ------------------------ Opus-based Graphical User Interface	Windows, Macintosh, Linux --------------------- Desktop computer, Workstation	Moderate	Large-scale	Supports planning, analysis and modelling of urban development/land use/transportation/ housing affordability/ environmentally sensitive habitats and greenhouse gas emissions
VisualBots http://www.visualbots.com/ -------------------- Closed source, EULA, Free	Microsoft.Net	Agents/ objects implemented as class constructs	Graphical user interface in Excel VBA (Visual Basic for Applications)	Microsoft.Net Compiler --------------------- Windows --------------------- Desktop computer	Simple/Easy	Light-weight/ Small-scale	Simulations in social and political science, economics, emergent behaviours, cellular automata, education/teaching
VSEit (Versatile Simulation Environment for the internet) http://www.vseit.de/VSEit09/ -------------------- Closed source, Free	Java	Agents/ objects implemented as Java classes	Java ------------------------ User-interactive Graphical User Interface (GUI) for model running	Java-enabled Internet browser --------------------- Desktop computer	Simple/Easy	Medium-scale	Social sciences (ecology and economy), object-oriented stochastic event-driven simulations (cellular automata), education/teaching
Xholon http://www.primordion.com/Xholon/about/abm.html -------------------- Open source, LGPL, Free	Java	Reactive behavioural agents/objects implemented as Java classes	XML/Java support for Unified Modelling Language (UML 2.1); Turtle geometry using an optional NetLogo-like syntax ------------------------ User-interactive Graphical User Interface (GUI) for model running	Java Runtime Environment -------------------- Windows, Linux, (any Java-enabled platform) --------------------- Desktop computer, Workstation	Moderate	Medium-scale	2D/3D simulations in cellular automata, biology, biochemistry, statistical modelling, controllers, and other embedded systems

implementation;

- Amount of effort/input required for the design and development of users' model;
- Computational modelling strength or scalability of the models developed through the use of particular toolkits;
- Assessment of coverage of application areas/domains covered by the ABMS tool;
- Brief description of the agent-based modelling and simulation functionality provided by each mentioned ABMS tool.

Most ABMS software tools contained in this survey are academic artefacts, open source and possess innovative modelling and simulation features, e.g., simplified modelling processes, technical support, efficient modelling functionalities, and user-friendly interfaces. In terms of the demands of programming knowledge and experience, ABMS toolkits often require users' to be proficient in the programming languages, such as: C/C++, Python, Java, Smalltalk, Basic; however commercially available suites are usually bundled with ready-to-use Application Programming Interfaces (APIs), add-ons and libraries that allow the audience to build and implement higher-level/fine-grain simulation models.

Table 1 provides an overview to the developers/programmers/ coders potentially looking for ideas to implement an ABMS soft-

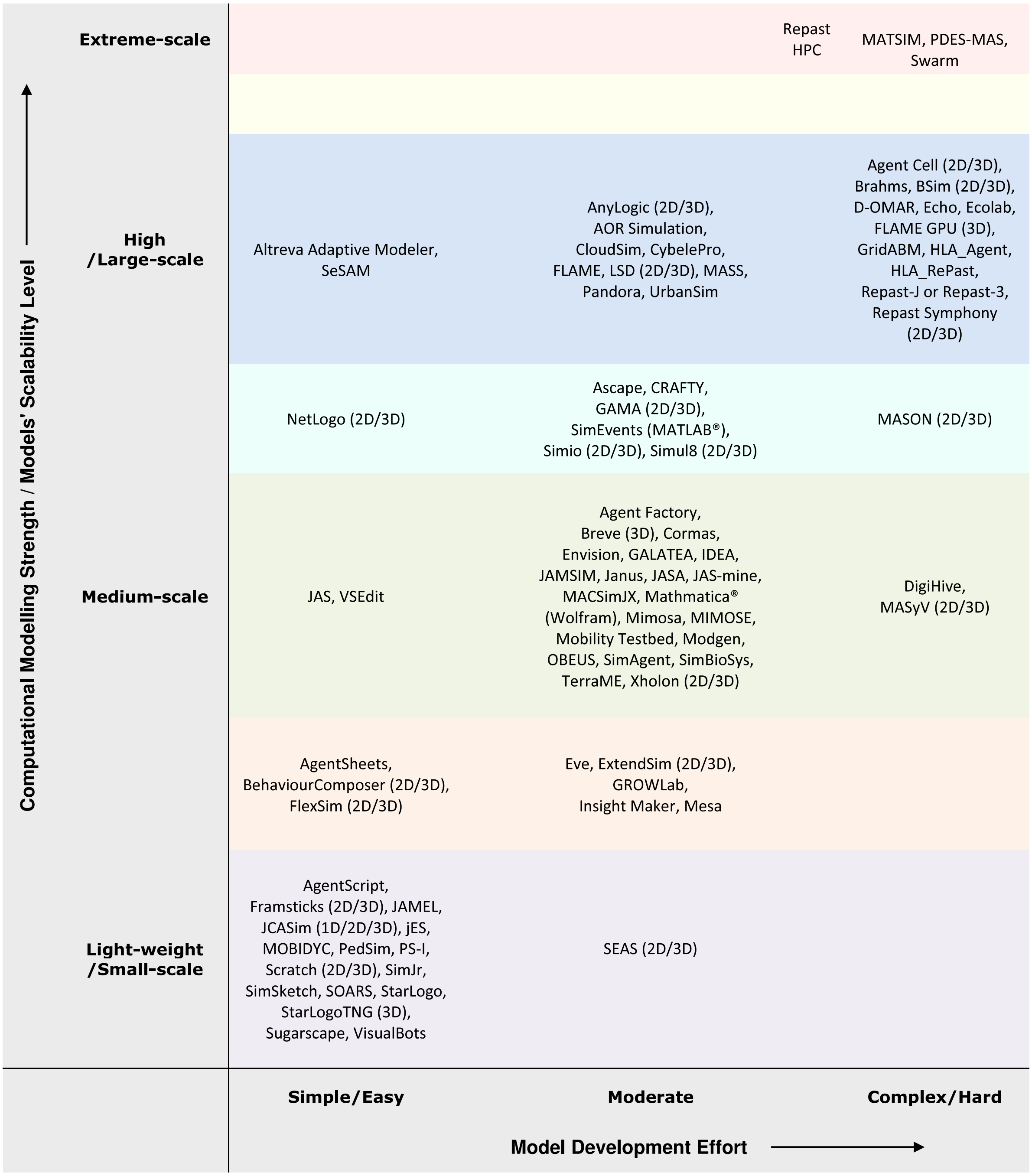
Table 2
Application domains covered by the ABMS tools.

ABMS scope or application domain	ABMS software tools
Cellular automata, Complex adaptive systems, Emergent complex phenomena in Biology/Medical sciences, Epidemiology, Artificial life (Evolutionary computation or genetic programming, Artificial intelligence, Neural networks, Robotics)	Agent Cell (2D/3D), AnyLogic (2D/3D), Ascape, BehaviourComposer (2D/3D), Breve (3D), BSim (2D/3D), DigiHive, Echo, EcoLab, FLAME, FLAME GPU (3D), Framsticks (2D/3D), GALATEA, GridABM, HLA_Agent, HLA_RePast, JAS, JCASim (1D/2D/3D), MASON (2D/3D), MASyV (2D/3D), Mathmatica® (Wolfram), Mesa, MIMOSE, MOBIDYC, PDES-MAS, Repast-J/Repast-3, Repast HPC, Repast Simphony (2D/3D), SEAS (2D/3D), SimAgent, SimBioSys, SOARS, Sugarscape, Swarm, TerraME, VisualBots, VSEit, Xholon (2D/3D)
Social & natural sciences, Dynamic computational Systems, Business, Marketing, Economics, Ecology, Healthcare, Planning & Scheduling, Enterprise and organizational behaviour, Traffic Situations (avoidance of traffic jams, light control, route choice)	Agent Factory, AgentScript, AgentSheets, AnyLogic (2D/3D), AOR Simulation, Ascape, BehaviourComposer (2D/3D), Brahms, Cormas, CybelePro, Echo, Envision, Eve, ExtendSim (2D/3D), FLAME, FlexSim, Framsticks (2D/3D), GALATEA, GAMA (2D/3D), GROWLab, HLA_Agent, HLA_RePast, IDEA, Insight Maker, JAMSIM, Janus, JAS, JAS-mine, jES, LSD (2D/3D), MASON (2D/3D), MASS, Mathmatica® (Wolfram), MATSim, Mimosa, MIMOSE, MOBIDYC, Modgen, NetLogo (2D/3D), Pandora, PDES-MAS, PS-I, Repast-J/Repast-3, Repast HPC, Repast Simphony (2D/3D), SeSAm, SimAgent, SimBioSys, SimEvents (MATLAB®), Simio (2D/3D), SimJr, SimSketch, Simul8, SOARS, StarLogo, Sugarscape, Swarm, UrbanSim, VisualBots, VSEit
Education/Teaching	AgentScript, AgentSheets, BehaviourComposer (2D/3D), ExtendSim (2D/3D), Framsticks (2D/3D), JAS-mine, MIMOSE, MOBIDYC, NetLogo (2D/3D), Scratch (2D/3D), SeSAm, SimSketch, Simul8, StarLogo, StarLogo TNG (3D), Sugarscape, VisualBots, VSEit
Cloud computing/Virtualised datacentres	CloudSim
Geographic Information System (GIS), Geographic Automata System (GAS)	Cormas, Envision, GAMA (2D/3D), Insight Maker, MATSim, OBEUS, Pandora, Repast-J/Repast-3, Repast HPC, Repast Simphony (2D/3D), SOARS, TerraME
Aviation, Flight or air-traffic control, Ground transportation/Mobility planning systems	CybelePro, D-OMAR, ExtendSim (2D/3D), FlexSim (2D/3D), MACSimJX, MATSim, Mobility testbed, SimEvents (MATLAB®), Simio (2D/3D), SimJr, Swarm, UrbanSim
Consumer products, Manufacturing, Production (factory based optimized plans for different requirements), Logistics/Distribution/Supply Chains (coordination, storage layout optimization)	AnyLogic (2D/3D), CRAFTY, ExtendSim (2D/3D), FlexSim (2D/3D), HLA_Agent, HLA_RePast, PDES-MAS, Repast-J/Repast-3, Repast HPC, Repast Simphony (2D/3D), SeSAm, SimEvents (MATLAB®), Simio (2D/3D), Simul8, Swarm
Urban Planning (accessibility studies with dynamic populations)	AnyLogic (2D/3D), CRAFTY, Envision, GAMA (2D/3D), JAS-mine, Modgen, OBEUS, UrbanSim
Microscopic pedestrian crowd or mapping passenger flow (market improvement & evacuation of buildings)	Brahms, HLA_Agent, HLA_RePast, PDES-MAS, PedSim, Repast-J/Repast-3, Repast HPC, Repast Simphony (2D/3D), SeSAm, Simio (2D/3D)
Political Phenomena	Ascape, PS-I, VisualBots
Military-combat/War-fighting/Air-defense Scenarios	ExtendSim (2D/3D), HLA_Agent, HLA_RePast, PDES-MAS, SEAS (2D/3D), SimEvents (MATLAB®), Simio (2D/3D), SimJr
Financial market's stocks/Securities, Macroeconomic activity	Altreva adaptive modeler, JAMEL, JASA
Large-scale parallel/Distributed computing clusters & high performance supercomputers	Agent Cell (2D/3D), Ecolab, FLAME, FLAME GPU (3D), GridABM, HLA_Agent, HLA_RePast, MATSIM, Pandora, PDES-MAS, Repast-J or Repast-3, Repast HPC, Repast Symphony (2D/3D), Swarm

ware, or researchers who need to develop prototype systems can comprehend the intended purpose and limitations or insufficiencies of reachable tools, without having to search the internet extensively. Table 1 tabulates each tool's technical features and specifications that have been taken from the developers' sites where the technical guides, manuals and ABMSs software itself are available for downloading. Quite often, the developers stop updating their ABMS software and sometimes the URLs (Uniform Resource Locator) no longer exist, therefore the Web-sites of all tools that are discussed here have been archived in the Wayback Machine [16] which is a digital log of the Internet's information and registers/maintains complete snapshots of all Web-links located under a single domain name. Thus, the proposed survey offers a reference summary which harnesses an archival system capturing those tools which have become obsolete or no longer exist, and provides information on the features and functionality of prior ABMS software that were once utilized extensively in the development of agent-based simulated prototypes and referred in the past research publications. This paper provides an updated ABMS review by integrating pointers to all the most relevant survey literature, and anticipates future extensions from the global ABMS community. The review evaluates simulation based packages and models and identifies their common traits and design considerations. Table 1 summarizes in alphabetical order the detailed comparison of the basic features of a considerable number of well-known ABMS tools.

4.2. Analysing ABMS toolkits

Comparing usability aspects of the toolkits involves many challenges as each one is unique and has been designed for distinct purposes. Some ABMS packages (Altreva Adaptive Modeler, AgentSheets, Envision, ExtendSim, Framsticks, Mathmatica® (Wolfram), MASS, MASyV, Mimosa, PedSim, Repast Simphony, SimEvents (MATLAB®), SOARS, StarLogo, Sugarscape, VisualBots, Simio, Simul8) have built-in support of visual intuitive graphical user tools facilitating model development via flexible drag-and-drop kind of interfaces, real-time visualisation via charting and plotting to comprehend the models' adaptation, evolution and functional profiles [50]. The majority of software in our study are freely available at no cost for academic and research purposes, are open source and compliant to lenient end-user licensing provisions. Whereas the sharewares have trial versions available, most are closed source, and have proprietary or restrictive license agreements. A lot of tools have comprehensive technical documentation, user manuals, tutorials, and public support mailing-lists.



Computational Modelling Strength / Models' Scalability Level	Simple/Easy	Moderate	Complex/Hard
Extreme-scale			Repast HPC MATSIM, PDES-MAS, Swarm
High /Large-scale	Altreva Adaptive Modeler, SeSAM	AnyLogic (2D/3D), AOR Simulation, CloudSim, CybelePro, FLAME, LSD (2D/3D), MASS, Pandora, UrbanSim	Agent Cell (2D/3D), Brahms, BSim (2D/3D), D-OMAR, Echo, Ecolab, FLAME GPU (3D), GridABM, HLA_Agent, HLA_RePast, Repast-J or Repast-3, Repast Symphony (2D/3D)
	NetLogo (2D/3D)	Ascape, CRAFTY, GAMA (2D/3D), SimEvents (MATLAB®), Simio (2D/3D), Simul8 (2D/3D)	MASON (2D/3D)
Medium-scale	JAS, VSEdit	Agent Factory, Breve (3D), Cormas, Envision, GALATEA, IDEA, JAMSIM, Janus, JASA, JAS-mine, MACSimJX, Mathmatica® (Wolfram), Mimosa, MIMOSE, Mobility Testbed, Modgen, OBEUS, SimAgent, SimBioSys, TerraME, Xholon (2D/3D)	DigiHive, MASyV (2D/3D)
	AgentSheets, BehaviourComposer (2D/3D), FlexSim (2D/3D)	Eve, ExtendSim (2D/3D), GROWLab, Insight Maker, Mesa	
Light-weight /Small-scale	AgentScript, Framsticks (2D/3D), JAMEL, JCASim (1D/2D/3D), jES, MOBIDYC, PedSim, PS-I, Scratch (2D/3D), SimJr, SimSketch, SOARS, StarLogo, StarLogoTNG (3D), Sugarscape, VisualBots	SEAS (2D/3D)	

Model Development Effort

Fig. 1. Ease of model development versus ABMS tools' computational modelling capacity or models' scalability level.

As the ABMS technology has become ubiquitous, the sophistication and scale of handy software for the modellers has grown larger too. Almost all the notable ABMS tools have primarily been designed to assist the builders in designing the agent-based models. An ideal simulation system should require minimal learning effort as well as provide flexible support to creating models and running robustly on any type of computing machine. As more complex algorithms, computing codes, tools, and libraries of ABMS are constructed, the incorporation of more sophisticated and extensible models has become feasible for the researchers [50]. In the past, conventional programming languages, such as: C, Smalltalk and Java, were mainly employed for the simulation models' design and development tasks. However, currently most of the ABMS software tools (Ascape, Breve, FlexSim, GAMA, GridABM, GROWLab, JAMEL, JAS, LSD, MASS, MASON, MASyV, NetLogo, PedSim, PS-I, Repast-J or Repast-3, Repast Simphony, Swarm, UrbanSim) are conceptual frameworks, though these provide several standard APIs, predesigned agent-templates and embedded libraries of procedures, which can be integrated in the custom formed programs obviating the need to program ones' own routines from scratch. The modellers create simulation models by making a series of calls, thereby invoking various built-in functions within the modelling toolkit [51]. Among these library-based platforms, MASON is particularly designed with execution speed a high priority [39]. LSD (Laboratory for Simulations Development) models are essentially C++ programs and as a consequence are extremely fast and powerful. Another breakthrough in ABMS computing is the development of collections of mature and stable packages assembled within the common standardized graphical Integrated Development Environments (IDEs), for building interactive simulation models using direct manipulation on intuitive visual programming IDEs. The best known examples in this context are Altreva Adaptive Modeler, AgentSheets, AnyLogic, FLAME, Framsticks, Mimosa, PedSim, Repast Simphony, SeSAm, StarLogo, and Sugarscape. The IDE approach also narrates inherent mechanism to interpret, compile and run the simulation models [51].

Table 2 contrasts application domains in a greater technical depth which are covered by various ABMS platforms. Here, the tools that provide three-dimensional modelling and simulation support can easily be distinguished. Clearly, a large set of existing tools support the modelling and simulation in social, natural, and human sciences; for instance, dynamic computational systems, business, marketing, economics, ecology, aviation, industrial control, manufacturing, planning and scheduling, enterprise and organizational behaviour and traffic situations. Computer simulation and modelling has a rich tradition in the education of Physics, Chemistry, Biology and other natural sciences. Many pedagogical and teaching related modelling and simulation software do not impose steep learning curves upon the novice users or non-specialists. Consequently, early career scholars do not need to formulate complex mathematical equations and learn the syntax and semantics of a modelling language or programming code to construct new simulation models. Additionally, as far as modelling/simulation related learning practices are concerned, there are in existence a number of ABMS hands-on instruments (AgentScript, AgentSheets, BehaviourComposer, FLAME, Framsticks, JAS-mine, MIMOSE, MOBIDYC, NetLogo, Scratch, SeSAm, SimSketch, StarLogo, StarLogo TNG, Sugarscape, VisualBots, VSEit) which incorporate simple easy-to-use interfaces and could be a good choice for educators, teachers, as well as novice users to learn how to implement light-weight simulation scenarios. However these systems tend not to upscale well to bigger and more complex models [51–53].

Fig. 1 depicts with clarity the ease in model development versus ABMS tools' computational modelling capacity or simulation models' scalability level. Other widespread ABMS software, like, Agent Cell, BSim, Breve, DigiHive, Echo, EcoLab, FLAME GPU, GridABM, JCASim, jES, MASyV, MOBIDYC, Pandora, Swarm, Xholon support prototyping sophisticated models with numerous agents and tangled geometrical shapes and rules, and are suited to high-level domains, such as, complex adaptive systems, over-complicated emergent phenomena in biology/medical sciences, cellular automata (mathematically describing processes inside the cells), and artificial life. Likewise, such extreme-scale simulations typically involve huge numbers of agents and as such, cannot be modelled on a simple personal computer due to the memory and storage issues. Hence, these simulations can be conducted on the workstations and high-end scientific computing systems employing some popular ABMS tools; for example, MATSIM, PDES-MAS, Repast HPC and Swarm all of which provide powerful computational modelling capabilities. Simulated testing of reference models and qualitative analysis of ten multi-agent platforms on high performance computing clusters with distributed and parallel cores has been presented in [31]. Table 2 concisely differentiates between the key features and functionalities indigenous to every ABMS software included in this review and serves as an aide for the judicious selection of one toolkit over another in a given situation or context.

5. Concluding remarks

This paper provides an in-depth insight into the agent-based modelling and simulation concepts, and formulates a broad-ranging crossover survey of the most recent state-of-art software agent-mediated computing technology and its incorporation within the modelling and simulation domain. Agent-supported modelling and simulation techniques are used for the representation of social, economic, ecological, meteorological, business and other similar systems in a software environment, to enable computer-based assistance in problem solving or enhancing cognitive capabilities. ABMS systems have fundamental similarities with certain traits of human societies and natural ecosystems and therefore, can effectively mimic their actions and can act as an appropriate technological vehicle for simulation tests, experiments and forecastings that would probably not be otherwise possible. Within this paper, a comprehensive comparison of the scientific simulation based packages and models has been performed on extracting their common features and design issues as well as dissimilarities. The key focus is to characterize almost the entire spectrum of currently available diverse array of agent-based modelling and simulation packages, and put these in a repertoire, thereby effectively distilling noteworthy features, merits, and demerits of these multifaceted application software. In this survey, we have taken into account the salient characteristics inherent to each ABMS tool, such as: license categories, software availability (freeware/shareware), source code specification, Integrated Development Environment (IDE) and the coding language utilised to craft agent-based simulation models, Application Programming Interface (API) or native libraries to accommodate the simulation models' construction and evolution process, nature or type of agent implementation, identification of operating system and compiler as well as hardware computing platform, users' model development input requirements, software's modelling power or scalability support available, and domain coverage of each ABMS toolkit.

The rationale for this paper is to help scientists and engineers in quickly assessing how they might choose and properly apply ABMS to their own research applications. There may be some limitations of this study. Though, we have investigated a large breadth of credible ABMS platforms, more subtle characteristics indigenous to each package may not be included. It is sometimes the case, that such opaque factors can critically influence one's decision to prefer one modelling and simulation tool over another. Examples of such might be the particular domain and special modelling requirements or a desire to compare one's results with another study which was undertaken in a particular package. Despite this, it is our hope that this comprehensive and up-to-date index of innovative ABMS software serves as a seminal reference to aid potential engineers, academics and researchers to readily make an informed selection as to an appropriate accessible agent-based modelling and simulation toolkit in-line with their interest, skills, and the inherent requirements of the application domain for their research prototypes.

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