Artif Intell Rev (2007) 28:305–342
DOI 10.1007/s10462-009-9105-x

Agent-based simulation of electricity markets: a survey of tools

Zhi Zhou · Wai Kin (Victor) Chan · Joe H. Chow

Published online: 12 July 2009

Abstract Agent-based simulation has been a popular technique in modeling and analyzing electricity markets in recent years. The main objective of this paper is to study existing agent-based simulation packages for electricity markets. We first provide an overview of electricity markets and briefly introduce the agent-based simulation technique. We then investigate several general-purpose agent-based simulation tools. Next, we review four popular agent-based simulation packages developed for electricity markets and several agent-based simulation models reported in the literature. We compare all the reviewed packages and models and identify their common features and design issues. Based on the study, we describe an agent-based simulation framework for electricity markets to facilitate the development of future models for electricity markets.

Keywords Agent-based simulation · Electricity market · Swarm intelligence · Artificial life · Adaptation

1 Introduction

Agent-based simulation (ABS) has received increasing attentions in recent years owing to its advantages in modeling large-scale complex systems. ABS is also commonly used to study the electricity market (EM) for operating a power system—"the most complex machine ever

Z. Zhou · W. K. (Victor) Chan (✉)
Department of Decision Sciences and Engineering Systems, Rensselaer Polytechnic Institute, Troy, NY 12180, USA
e-mail: chanw@rpi.edu

Z. Zhou
e-mail: zhouz@rpi.edu

J. H. Chow
Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180, USA
e-mail: chowj@rpi.edu

invented" (Amin 2003)—because of its capability of modeling the complex behaviors of various participants in a large-scale EM. Despite the popular use of ABS in EMs, a systematic literature review in this area is not readily available. This paper reviews existing popular agent-based systems for EMs. Based on the review, this paper also provides an ABS framework for EMs.

We start by providing an overview of electricity markets. We then study several general-purpose ABS tools to introduce some background of ABS and summarize several guidelines for choosing the ABS development platform for EMs. These general-purpose ABS tools include SWARM, Recursive Porous Agent Simulation Toolkit (Repast), Multi-Agent Simulation of Neighborhood (MASON), StarLogo, and AnyLogic. Next, we review four popular ABS packages for EMs. The first one is the Simulator for Electric Power Industry Agents (SEPIA), which is one of the earliest efforts of using ABS for EMs. The second is the Electricity Market Complex Adaptive Systems (EMCAS), which is a powerful EM ABS package. The third and fourth are, respectively, the Short-Term Electricity Market Simulator-Real Time (STEMS-RT) and the National Electricity Market Simulation System (NEMSIM), both of which contain some state-of-the-art features. We also survey several EM ABS models reported in the literature. These include: two ABS models for the EMs in the United Kingdom; the Agent-based Modeling of Electricity System (AMES), which is an open-source agent-based framework for EMs; the Multi-Agent System that Simulates Competitive Electricity Markets (MASCEM), which studies competitive electricity markets; an ABS that studies the dynamics of a two-settlement EM consisting of a forward market and a spot market; and the PowerACE that examines the CO_2 emission trading market. Because some packages or models are proprietary, full documentation of all reviewed software and models are not available. Therefore, our review is conducted based on the documents and resources available to the general public (see the references). We compare all the reviewed packages and models. Finally, by summarizing the features and design issues of the reviewed packages and models, this paper presents an ABS framework for EMs to facilitate the development of future EM ABS models.

This paper is organized as follows. Section 2 gives an overview of deregulated EMs. Section 3 surveys general ABS tools and compares them based on different evaluation criteria. Section 4 introduces four ABS packages for EMs and several research purpose EM ABS models. Section 5 provides a detailed study on all the reviewed packages and models. Based on this study, Sect. 6 presents an ABS framework for EMs. Finally, Sect. 7 draws some conclusions and suggests possible research extensions. Acronyms frequently used in this paper are listed below:

ABS:	Agent-based simulation
ALF:	Argonne load flow
AMES:	Agent modeling electricity system
DES:	Discrete-event simulation
EMCAS:	Electricity market complex adaptive systems
EM:	Electricity market
GLR:	Generator of last resort
ISO:	Independent system operator
MASCEM:	Multi-agent system that simulates competitive electricity markets
MASON:	Multi-agent simulation of neighborhood
MCP:	Market clearing price
MIS:	Market information system

NEMMCO:	National electricity market management company limited
NEMSIM:	National electricity market simulation system
NETA:	New electricity trade arrangement
NSP:	Network service provider
OASIS:	Open access same-time information system
Repast:	Recursive porous agent simulation toolkit
SEPIA:	Simulator for electric power industry agents
SMP:	System marginal price
STEMS-RT:	Short-term electricity market simulator-real time
TLP:	Transmission line provider

2 Electricity market overview

During the last 20 years, a process has been undergoing worldwide to restructure electrical power facilities and liberalize the markets for services based on these facilities. This process moves the electricity industry from vertically integrated monopolies to multiple independent companies and replaces the centralized cost-based market to supply- and demand-based competition. The major goal of this reform is to promote energy conservation and alternative energy technologies and to reduce oil and gas consumption through technology improvement and regulations (FERC 2006).

In the restructuring process, a power system is divided into multiple components including generation, transmission, distribution, and system operation, which are the major participants of an EM. In Sects. 2.1, 2.2, 2.3 and 2.4, we briefly introduce the functionalities and roles of these components (entities). Multiple submarkets may coexist in one EM, such as the energy market, installed capacity (ICAP) market, and emission market. We shall also briefly discuss these markets in Sects. 2.5, 2.6 and 2.7. Figure 1 depicts the relationships among the market participants and different types of submarkets within an EM. Their detailed relationships are to be discussed further in Sect. 6 (see, e.g., Fig. 11)

2.1 Customer company

In general, a customer company plays two roles in the market: it is the *customer* in a wholesale market and the *supplier* in a retail market, distributing electric services to end-users. Major activities of a customer company include forecasting the load demand in its service area and making contracts with other market participants to purchase electricity to satisfy the load demand. Customer companies like this are called competitive retailers (CRs), which means that they have to compete with other CRs for customers because customers can switch among different CRs. Besides CRs, at the current deregulated stage, there is another kind of customer companies called non-opt-in Entities (NOIEs). An NOIE is a municipally owned utility and does not offer choices to customers.

2.2 Generation company

Power generation companies (or simply, generators) are the suppliers in an EM. In the wholesale market, competing generators sell their electricity through an auction market or bilateral contracts. Generators need to determine their daily power generation schedule, plan their capacity expansion, and deal with potential issues associated with the production of electricity, such as CO_2 emission.

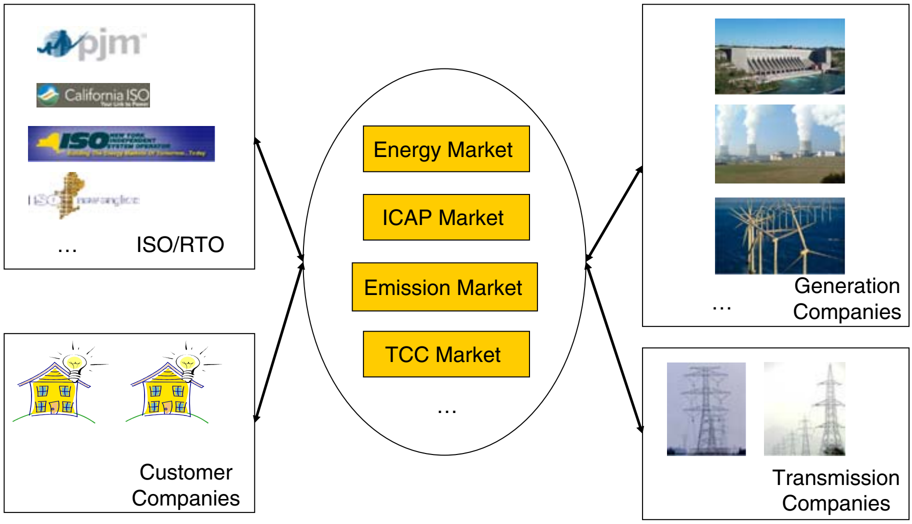

Fig. 1 Market participants and submarkets in an electric power market

2.3 Transmission company

The restructure of the power system in the United States requires that the transmission systems be accessible to all suppliers (FERC 2006). Under this requirement, a transmission company becomes an organization that owns, maintains, and operates transmission assets for profit, but under regulation. It has the ability to propose and build new transmission facilities. In a deregulated market, a transmission company maintains a reliable transmission system to transmit electrical power to load areas.

2.4 Independent system operator (ISO)/regional transmission operator (RTO)

An independent system operator (ISO) is an organization that coordinates, controls, and monitors the operations of an electric power system in its service territory. It is formed at the direction and recommendation of the FERC. It is possible to have one ISO monitoring a single state, for example, the New York Independent System Operator (NYISO), or one ISO operating multiple states, such as ISO-New England. Similar to an ISO, a regional transmission operator (RTO) coordinates, controls, and monitors the electric power transmission network over a wide area across multiple states, for example, PJM.

Besides the aforementioned functionalities, some ISOs/RTOs also act as regulators in their electricity markets, including the wholesale markets. In a wholesale market, the ISO/RTO sets up the market and clears the market based on the bids submitted by the loads and suppliers. The ISO/RTO also needs to ensure market fairness and efficiency by applying various market rules. Most ISOs/RTOs are nonprofit corporations based on the governance models developed by FERC.

Besides NYISO and ISO-New England, other ISOs/RTOs include Midwest ISO (MISO) and the California ISO (CAISO). Common elements in these ISOs include: (1) real-time balancing markets, (2) resource regulation markets, (3) spinning reserves markets, and (4) financial tools for hedging against congestion rent (Goldman et al. 2004).

2.5 Energy market

The energy market is mainly used for trading electricity. Therefore, the commodity of this market is electricity. Typically, two types of instruments for trading electricity are used: pool and bilateral contracts. In a pool contract market, producers and buyers submit their bids, and the market is cleared by a market operator (such as the ISO). The operator also announces the clearing prices for the next day based on the amount of the supply and demand bids submitted by the producers and buyers. Because of its main usage in the day-ahead market, the pool contract market is considered as a short-term trading market. On the other hand, bilateral contracts are usually used by companies to hedge against the risk of daily price volatility. The contract periods can cover 6 months or more. As a result, bilateral contract market is considered as a medium-term contract market.

2.6 ICAP market

The objective of the ICAP market is to secure an adequate amount of generation to supply load, which also encourages new capacity investments. Electricity demand normally increases yearly. To guarantee the reliability and security of the electricity system, mechanisms must be provided to encourage generation companies to invest new capacity to meet the ever-increasing demand. The ICAP market is one such mechanism to encouraging capacity investments. The commodity of the ICAP market is the installed capacity of generation companies. In an ICAP market, generation companies which commit to provide certain amount of supply are paid by customer companies. The price is cleared by the market operator (i.e., ISO). Generation companies therefore have incentives to make long-term investments on generation capacity expansion.

2.7 CO_2 emission market

The CO_2 emission market is a mechanism to limit the emission of CO_2. The commodity of this market is the quota of CO_2 emission. The cap-and-trade system is used to reduce the emission of greenhouse gases. In this market, generation companies can sell their emission allowance if it falls below their upper limits. The goal of this system is foster cost-effective generations in view of CO_2 emissions.

3 Review of agent-based simulations

ABS has been a rapidly growing area in the past decade. The fundamental approach of ABS is to simulate real-world systems with a group of interacting autonomous agents modeled as computer programs. One of the main objectives of ABS is to study the interactions of the agents and/or emerging collective behavior, such as uncontrolled self-cooperation, division of labor, foraging, and nest building (Bonabeau et al. 1999). The theoretical foundation of ABS lies mainly in *Complex System Modeling* (CSM), *Artificial Life* (AL), and *Swarm Intelligence* (SI).

This section reviews general ABS systems. The goal of this background-introduction section is to discuss the main advantages and possible limitations of existing ABS systems developed for general purposes. ABS systems for EMs are to be reviewed and discussed in subsequent sections.

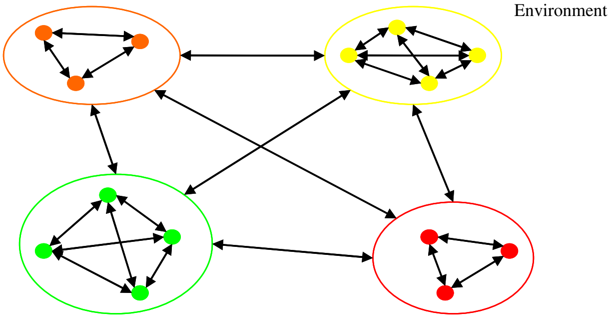

Fig. 2 An agent-based simulation system

3.1 Overview of ABS systems

An ABS system is a system that contains autonomous agents. There are three basic elements in an ABS system: agents, environment, and rules.

Environment is the space where agents situate. It is usually in two forms: networks or spatial space divided into cells. It can be spatially heterogeneous and evolve over time. Rules are the guidance for system state transitions. In general, there are three types of rules: agent-agent rules, agent-environment rules, and environment-environment rules. The agent-agent rules are designed for agents' actions and interactions. The agent-environment rules guide the agents on how to respond to changes in the environment. When the environment is heterogeneous, the environment-environment rules define how environments influence each other.

Figure 2 gives a schematic illustration of an ABS system. The whole rectangle represents a predefined environment and each of the four ellipsoids denotes a group of agents symbolized by small dots. Usually, agents in an ABS system bear objectives and intelligence. They have the ability to extract information about its internal and external states. Based on the awareness of these states, they make decisions or take actions in accordance with some predefined rules. In a large population ABS system, agents can be separated into groups based on their common characteristics or objectives (e.g., the four ellipsoids in Fig. 2). Usually, a majority of the agents have access only to local information and can only interact with their neighbors. In an ABS simulation model, agents are allowed to interact with each other from time to time (or iteration to iteration), driving the simulation model to evolve and possibly exhibit emerging behavior or patterns. As a result, insights about the dynamics of the underlying system may be obtained.

Because of the aforementioned characteristics, the design of an ABS involves many aspects, including communication protocols and languages, negotiation strategies, software architecture, and formalisms. For instance, in an ABS system interactions and communications among agents require the support of a set of communication protocols and languages (Steels 1998). Pioneer work includes the Knowledge Query and Manipulation Language (KQML) (Finin et al. 1994) and the Foundation for Intelligent Physical Agents (FIPA) (FIPA 1997). Negotiations among agents are a way of allocating resources and possibly a mechanism for letting agents to reach their objectives. There are two types of negotiations: cooperative negotiations and competitive negotiations. In a competitive negotiation, agents negotiate to optimize their own utilities (or rewards); while in a cooperative negotiation, agents may negotiate to form a coalition to maximize their collective utilities. Examples of the implementation of negotiations in an ABS simulation can be found in Zhang et al. (2003, 2004), Klusch and Gerber (2002) and Wang et al. (2003).

3.2 Common features of agents

An agent can be as simple as a single variable within a computer program or as complex as an intelligent object such as a human being involving possibly an infinite number of states, decisions, and actions/reactions. Therefore, the precise definition of "agents" is domain dependent (Macal and North 2005). From the software engineering perspective, an agent could be an encapsulated computer system (Wooldridge 1997). In the artificial intelligence domain, agents are sometimes referred to as "people" of artificial societies (Epstein and Axtell 1996). In the areas of optimization and heuristic algorithms, an agent could be a metaphor (e.g., a piece of computer code) representing a real object of the underlying system, such as a molecule in a biological system, an ant in an ant colony, or a fish in a school (Bonabeau et al. 1999).

Features of agents also vary in their applications; details can be found in, e.g., Haverkamp and Gauch (1998), Boudriga and Obaidat (2004) and Borshchev (2005). In the following, we shall review some of the common features of agents from the electric power market standpoint. These features such as internal states and autonomy should allow the agents to make decisions independently based on their objectives, awareness of the current state, and the environment.

From the electric power market standpoint, we consider agents to have the following features:

(1) *Autonomy*: an agent is an independent entity of the underlying system. It communicates and interacts with other agents, but makes its decision without external control by its peers or administrative agents. Although each agent makes its own decisions, its decisions depend heavily on the interactions with other agents or the environment. Furthermore, in an ABS system, agents and the environment follow some pre-specified rules. After communicating and interacting with other agents and/or the environment, an agent would take actions that comply with its roles. Therefore, the autonomy of an agent is role oriented.
(2) *Heterogeneity*: every agent in an ABS system could be different and maintains its own characteristics. An ABS system such as an EM ABS may consist of several groups of agents such as generation companies, consumer companies, and an ISO. The roles of agents in different groups are different. Furthermore, agents in the same group can represent different entities. For instance, while the agents of generation companies serve the same role of electricity generation in EMs, each generation company has its own features such as production capacity and production cost.
(3) *Adaptation*: each agent should be adaptive to its underlying environment. In other words, an agent must make adaptive decision according to its current states and the changing conditions in its environment. For example, in an EM each generation company, in order to secure its own "benefit" for maximum profit, should adaptively adjust its selling price based on relevant factors of the environment including the demand, seasons, and actions of its competitors.
(4) *Social ability*: agents should have the ability to communicate and exchange information. This ability provides a basic mechanism for agents to interact with other agents or human in order to promote their objectives or help others with their activities (Wooldridge and Jennings 1995). In an EM, the social abilities of a generator agent allow it to submit

bids, retrieve market information, and exchange information with the ISO, customer companies, or other generators.

In addition to the above main features, other desirable features include *interactivity, communicability*, *mobility*, *flexibility*, and *concurrence*. Finally, although each agent is an autonomous unit, both individual agents and the agent-based system are *goal oriented*; their goals direct their behavior and decisions. For example, the bidding strategies of generation companies are directed by their goal of profit maximization. The goals of an ISO agent to ensure market fairness and design efficient market rules or instruments. Customer companies' decisions on demand bids could be influenced by their objectives on trying to reduce payment without sacrificing the quality and reliability of the electrical supply service.

3.3 Advantages of agent-based simulation

Two advantages of ABS in modeling autonomous systems compared with traditional discrete event simulation (DES) are as follows: first, ABS could conveniently model the complex behavior of system participants (such as autonomy, intelligence, and reactions) in the underlying environment; and second, ABS is particularly suitable for large-scale systems involving various types of interacting system participants with distinct roles, functionalities, behavior, and decisions, which depend on the participant's objectives and interactions with other system participants.

From the EM standpoint, the ABS technique is a more suitable modeling and analysis approach than the conventional DES approach. This is because of the complexity of the EM system itself and the behavior emerging from the interactions of its market participants. Many issues could arise in studying an EM, such as asymmetric information among participants, imperfect competitions, strategic interactions, individual learning behaviors, and possibility of multiple equilibria (Tesfatsion 2006). Many of these issues are difficult to model or analyze by conventional modeling techniques, such as an analytical approach, because conventional modeling techniques usually require restrictive assumptions and strong constraints (Weidlich and Veit 2008). On the other hand, ABS when applied to EMs can facilitate the investigation of the effects of various behavior, interactions, or strategic decisions from different market participants. In fact, an EM involves many participants with various roles. Each participant could be responsible for many strategic decisions and its behaviors have direct or indirect impact on other participants and/or the whole EM system. Successful applications of ABS in various disciplines can be found in Davidsson (2001) Gotts et al. (2003), Macal and North (2005), Macal and North (2006) and Railsback et al. (2006).

3.4 Review of general-purpose agent-based simulation systems

This section describes some general ABS packages, which can be used to develop ABS models for various kinds of systems including, but not limited to, EMs. Some of the EM ABS systems to be studied in Sect. 4 are developed using these general-purpose ABS packages. One can of course create his/her own EM ABS model using these packages. Therefore, the review of these packages would serve as a prelude to the more in-depth discussion of the specific EM ABS systems in Sect. 4.

In general, ABS packages can be divided into two types: toolkits and software (Castle and Crooks 2006). Toolkits provide libraries with some specific functions designed for ABS. Most toolkits have been developed by academic research centers/groups and contain some state-of-the-art features. Many toolkits are open source, but some free-for-use toolkits do not provide access to the source code. One drawback of many toolkits is the lack of professional

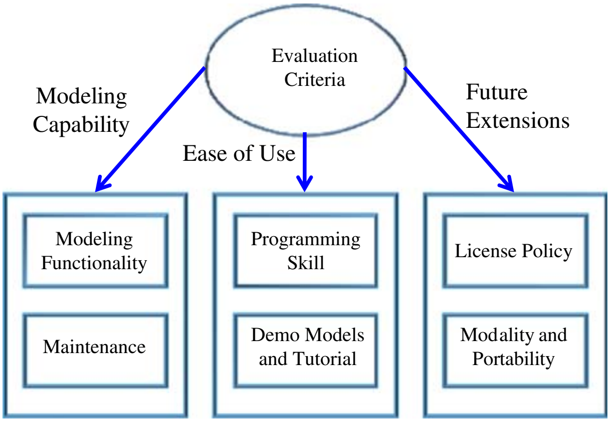

Fig. 3 Evaluation criteria for agent-based systems

and reliable technical support. Popular ABS toolkits include *SWARM*, *Repast*, *MASON*, *StarLogo*, and *NetLogo* (see Minar et al. 1996; Samuelson and Macal 2006; MASON Homepage 2007; Resnick 1994; NetLogo Homepage 2007, respectively, for details about these toolkits).

Compared with toolkits, ABS software provides relatively complete modeling functionalities, professional technical support, user-friendly interfaces, and simplified modeling process. In terms of the requirement of programming experience, toolkits usually require proficient skills in programming languages such as Java, Basic, or C++, while commercial software usually provides ready-to-use functions and allow users to build and implement simulation models at a higher level. Two popular ABS software packages are *AgentSheets* (Repenning 1993) and *AnyLogic* (Borshchev et al. 2002). Criteria for evaluating general ABS packages can be divided into three groups: modeling capability, ease of use, and future extensions. The evaluation framework for general ABS packages using these criteria is presented in Fig. 3.

In general, modeling functionalities and maintenance services are important considerations for selecting an ABS package. In particular, if a package is actively maintained and upgraded, its modeling functionalities will grow. Obviously, the license policy of ABS packages together with its modularity and portability can be used to measure its potential for future extensions. Finally, the requirement of programming skills and the availability of demonstration models and tutorials reflect the ease of use of a package. In practice, it may be difficult for an ABS package to meet all these criteria. If one focuses attention on EMs, then because of their high degree of complexity, one might consider the modeling capability as one of the most important criteria. The extensibility or ease of use is also an important factor to consider. In many cases, the choice of a general ABS package is made among the most popular packages. The well-known ABS packages to be reviewed here are classified into three groups (Castle and Crooks 2006): open source toolkits, free-for-use toolkits, and licensed commercial products dictated by license policies and future upgrade criteria.

In the following, we first review three well-known open-source toolkits: *SWARM*, *Repast*, and *MASON*. Purposes and basic features of these toolkits are somewhat similar. *SWARM* was developed by the Santa Fe Institute in 1996 (Davidsson 2001; Minar et al. 1996). A basic SWARM simulation model consists of a swarm (population) of agents, which interact with each other through discrete events generated by each agent. SWARM utilizes object-oriented techniques to model each agent and its states, which are good for future extensions.

To build a simulation model in SWARM, each agent is created using the "*SWARM library*" and is instantiated as an "object" in the system. There are three components in the SWARM libraries including *Simulation Libraries*, *Software Support Libraries*, and *Model Specific Libraries*. In the Simulation Libraries, there are several sub-libraries, among which the "*SwarmObject*" library is used to define the various types of agents, while the "*Activity*" library provides a schedule of activities (discrete events) to be implemented by the corresponding agents.

SWARM has moderate modeling functionalities developed and maintained by the SWARM Development Group (SDG). Regarding the ease of use, SWARM provides some demonstration models and tutorials to help users to get familiar with its features; but it lacks a user-friendly environment and requires proficient programming skills. SWARM is regarded as one of the earliest ABS toolkits for building simulations of complex adaptive systems.

Recursive Porous Agent Simulation Toolkit (*Repast*) (North et al. 2006) is another popular open-source toolkit and is currently maintained by the Argonne National Laboratory (2007). The main components of *Repast* include Engine module, Logging module, Interactive Run module, and Batch Run module, Adaptive Behavior module, and Domains module. The *Engine module* is designed to control the activities of each agent. The *Logging module* is used to record simulation results. The *Interactive Run module* provides a tool for users to control the simulation run and the*Batch Run module* can be used to set up a batch of automatic simulation run. The *Adaptive Behavior module* is designed to model adaptive behaviors of each agent. The learning techniques involved in this module include genetic algorithms (GA), artificial neural networks (ANN), and other artificial intelligence (AI) techniques. Finally, the *Domain module* provides specific simulation functions for particular applications such as social systems and geographical information systems (GIS). There are three versions of Repast including *Repast for Java*, *Repast for Python*, and *Repast for Microsoft.net*.

The modeling capability of Repast is high as shown in the literature. Indeed, one of the most comprehensive ABS systems for EMs, *EMCAS* (see Sect. 4.2), is developed using Repast (Conzelmann 2006). As for the ease of use, Repast provides many agent templates and examples. Nevertheless, Repast does require a certain level of programming skills if one tries to model a complex ABS system.

Multi-Agent Simulation of Neighborhood (*MASON*) (Luke et al. 2004, 2005) is developed by the George Mason University's (GMU) Evolutionary Computation Laboratory and Center for Social Complexity (George Mason University 2007). MASON is an ABS package for building platform-independent systems. The framework of MASON includes two modules: *Simulation Model* and *Visualization Tool*. As a core module in MASON, the Simulation Model mainly consists of object-oriented agents and their discrete-event schedules. The modeling functionalities of MASON in modeling large-scale complex systems are not as comprehensive as those in SWARM and Repast. When it comes to extensibility, MASON is developed purely in Java and has good modularity and portability. MASON also requires proficient programming skills.

StarLogo (Resnick 1994, 1996) is a free toolkit developed by the Media Lab at MIT (MIT 2007). Originally designed for education use, StarLogo is a tool for studying the behavior of decentralized systems. It does not adopt an object-oriented framework, nor does it provide its source code, and therefore future extensions and modeling capability are less flexible than other packages. However, a good feature of StarLogo is its ease of use with many demonstration models and supporting documents. Most of the limitations in StarLogo have been addressed in an improved version, called *NetLogo*, which is developed by the Center for Connected Learning and Computer-Based Modeling at the Northwestern University. NetLogo is an Internet version of StarLogo and its functionalities can be extended through APIs.

Finally, *AgentSheets* and *AnyLogic* are two well-known proprietary ABS packages. In general, these commercial products are easy to use with a user-friendly interface and good supporting documents and tutorials. Currently, AgentSheets (Repenning 1993; Repenning and Citrin 1993) is for educational use and its modeling capability is less comprehensive than other packages. The requirement of programming proficiency in using AgentSheets is not as high as other packages, making it a good package for novice users to build moderate-size ABS models.

AnyLogic (Borshchev et al. 2002) is a simulation package developed by *XJ Technologies Company*. AnyLogic supports three simulation modeling methodologies: DES, ABS, and system dynamics. AnyLogic version 6 is based on the Eclipse framework, which facilitates model developments and cross-platform applications. Features of AnyLogic include the following. First, simulation models created by AnyLogic are purely java applications that are portable and can readily be converted into java applets, allowing remote access of the models. The models also have open architecture and interfaces for connecting to databases. Second, AnyLogic provides statistical tools and data analysis objects for analyzing simulation results and visualizing dynamically changing data during the execution of a simulation. Third, it uses the optimizer "*OptQuest*" for optimization of simulation models. Fourth, it provides interactive 2D and 3D animations. In short, AnyLogic provides a variety of functionalities for developing ABS models and is relative easy to use compared with other open-source toolkits. It also provides demonstration models in different domains to show its wide range of applications, for example, manufacturing, healthcare, effects analysis, predictive modeling, business strategy analysis, transportation, sociology, economics, urban dynamics, supply chain, electric power grids, computer and telecom networks, logistics and warehousing, dynamic systems controls, complex adaptive systems, and social networks (Coensys Inc 2007).

In summary, the main advantages of AnyLogic include powerful modeling capabilities, ease of use (such as user-friendly interfaces, simplified modeling process, and professional supporting documents), and successful deployment in many applications. Although the extensibility of AnyLogic models depends on the license policy, future extensions are still possible as it is programmed in Java and provides interfaces to low-level programming environments.

4 ABS models for EMs

As outlined in Sect. 2, EMs have distinct characteristics (such as physical transmission infrastructure, various types of intelligent market participants and their interactions, decision making and adaptation) that would be better modeled by an ad-hoc ABS package designed especially for EMs. In this section, four well-known ABS packages for EMs are introduced: SEPIA, EMCAS, STEMS-RT, and NEMSIM. Reviewing some of the main features of these ABS systems will help the identification of common features and functionalities of ABS tools for EMs and ultimately facilitate our discussion on the ABS framework for EMs in later sections.

4.1 Simulator for electric power industry agents (SEPIA)

SEPIA (Harp et al. 2000) is developed by the Honeywell Technology Center (HTC 2007) and the University of Minnesota. It is a specific ABS EM tool for developing EM ABS models with the objectives of gaining insights about the behavior of system participants and their impacts on EMs. The principal physical components simulated in SEPIA are: Zones, Physical Generators, Generation Companies, Generator of Last Resort (GLR), Consumer Load,

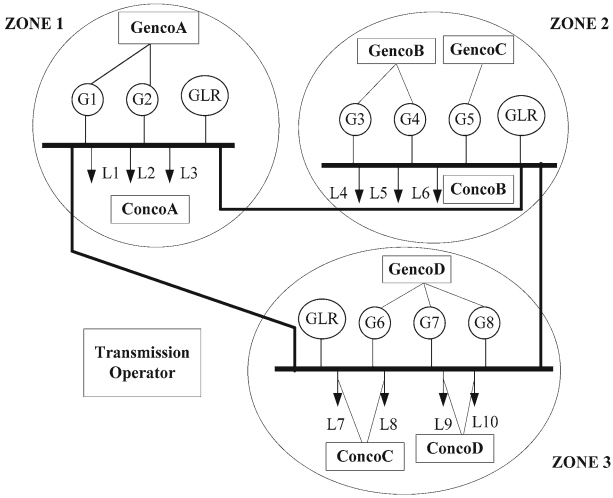

Fig. 4 The physical system structures of SEPIA (Harp et al. 2000)

Consumer Companies, Transmission System, and Transmission Operator. Figure 4 depicts the physical system structure of SEPIA (Harp et al. 2000).

In this subsection, four important design issues in SEPIA are presented separately, which are physical structures, the definition of agents and their interactions, physical models, and decision making and adaptation. Finally, its features and possible limitations are summarized.

4.1.1 Physical system structures

Regarding the physical system structure, SEPIA makes the following assumptions. First, each *zone* represents a local region in a real EM and each zone has exactly one bus for all power transmission from or to this region. Second, each *Generation Company* (along with its generators) and each Consumer Company (including its consumer loads) are confined in a zone (i.e., a specific local region). Third, each zone has a *Generator of Last Resort* (GLR), which has unlimited power capacity but at a price much higher than that of the other generators. Finally, it assumes unlimited transmission capacity within the same zone from a Generation Company to any individual Consumers. However, for any inter-zonal transactions, transmission constraints must be checked by the *Transmission Operator*. Although SEPIA has made several simplifications using the above assumptions, its physical system structure has captured the most common situations in a real EM system. Moreover, these simplifications are reasonable considering the fact that SEPIA is one of the earliest ABS tools for EMs.

4.1.2 Agents and interaction

All major market participants in SEPIA are modeled as agents, which include Generation Companies, Consumers, Consumer Companies, and Transmission Operator. Figure 5 depicts the interactions among these system participants (i.e., agents). It is noted that SEPIA does not include an independent system operator (ISO), which in a real EM, is an independent non-profit organization for coordinating, controlling, and monitoring regular operations of the electric power system and market.

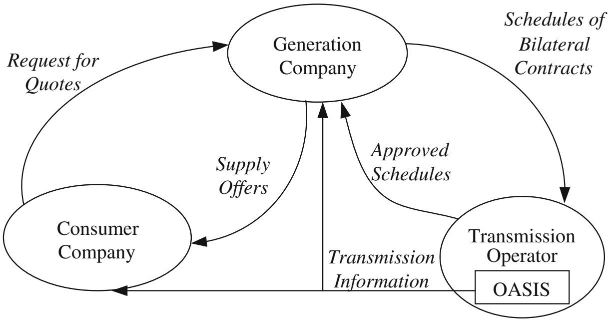

Fig. 5 Main interactions among principal agents in SEPIA

The roles of Consumer Companies in SEPIA include the following: collect load demands from customers to form the overall final load schedules; interact with Generation Companies to setup bilateral contracts; send request for quotes (RFQ) to Generation Companies; and receive responses from Generation Companies in the format of supply offers including price and quantity. Before the final decision of any bilateral contract is made, each Consumer or Generation Company can refer to the *Open Access Same-Time Information System* (OASIS) for transmission information. Once bilateral contracts are made with Consumer Companies, each Generation Company sends the corresponding transmission request to the Transmission Operator for approval and receives the approved schedules. The Transmission Operator collects the schedules requested by Generation Companies and determines the final transmission schedules after checking system security criteria.

There is a special agent called the *Generator of Last Resort* (*GLR*) in SEPIA. Each zone has exactly one GLR. The generating capacity of GLR is infinite, but its selling price is much higher than that of the other generators. This price is the same for all GLRs in different zones and is a model parameter configurable by the user. The GLR in each zone only responds to requests from Consumer Companies in the same zone. The main role of a GLR is to serve any unsatisfied load under the following two circumstances. First, when a Consumer Company does not receive enough quotes from Generation Companies in the bidding process, it will turn to the GLR in its region to fill the shortfall. Second, when any request for transmission quotes submitted by a Generation Company is cut back by the Transmission Operator, the Generation Company will need to purchase from the GLR through the "unsatisfied" Consumer Company in that region. Because the electricity price in the GLR is much higher, GLR is indeed the "last resort" for both Consumer Companies and Generation Companies. The GLR is a special agent in SEPIA and does not commonly exist in every EM.

Finally, *OASIS* is a database that provides real-time transmission information in SEPIA. It is owned and updated by the Transmission Operator. Transmission data for each approved transaction (the start time, length, and assigned lines for transmission) is updated and stored in the OASIS in real time. In this process, the Transmission Operator acts as an independent coordinator and adopts the first-come-first-serve rule for any requested schedule. Both Consumer Companies and Generation Companies have access to this database. Thus, the bilateral schedules can be revised according to the most updated transmission data stored in the OASIS.

4.1.3 Physical models of SEPIA

In SEPIA, a physical model for the load of an individual consumer is generated as follows: first, select a typical 24-h load curve for any individual load with Loadcurve(i, t) being the load for hour t at day d of individual i; and then, the final load for hour t of day d for an individual consumer i is uniformly distributed over the interval between minMW$(i)\times$ Loadcurve(i, t) and maxMW$(i)\times$ Loadcurve(i, t), where minMW(i) and maxMW(i) are the minimum and maximum load for individual i. The total loads of Consumer Company k at hour t of day d are the sum of all individual customer loads at hour t of day d. SEPIA also provides the *cost model of generators*. The cost of producing p MW electricity power is calculated using

$$\text{MBTu}(p) = \text{no-load cost} + \int_{\text{min MW}}^{p} \text{incremental fuel rate}(\rho)\mathrm{d}\rho$$

This cost model consists of "no load cost" and the load cost from minimum MW to p MW. Usually, the first-order derivative, the *incremental fuel rate*(ρ), is used to describe the fuel rate. The allocation of the MW output of generators in a Generation Company is carried out by "*economic load dispatch* (*ELD*)." The overall objective of ELD is to minimize the production cost subject to the load demand.

Finally, for the *physical transmission*, SEPIA uses both AC and DC models. Two security $(n-0)$ and $(n-1)$ tests are conducted by the Transmission Operator to check the transmission capacity. First, the $(n-0)$ test answers the following question: if there is a new transaction between zone n to zone m, what is the corresponding change to the flow in line *ij*? In SEPIA, the added amount of power flow in line *ij* is equal to $PTDF_{ij,nm} \times NewMWtransaction_{nm}$, where $PTDF_{ij,nm}$ is the *Power Transfer Distribution Factor* (a constant factor) and $NewMWtransaction_{nm}$ is the amount of the new transaction from zone n to zone m. Next, the $(n-1)$ test mainly concerns with the question of what the flow change will be in line *ij* when there is a loss in line *rs* between zone n to zone m. Similarly, the added amount of power flow in line *ij* is $LODF_{ij,rs} \times MWflow_{rs}$, where $LODF_{ij,rs}$ is the *Line Outage Distribution Factor* (a constant factor) and $MWflow_{rs}$ is the amount of electricity power flow originally allocated to transmission line *rs*. Furthermore, when both the new transaction and the loss of a specific line are considered, the flow change in line *ij* is calculated as below.

$$\Delta MWflow_{ij} = (PTDF_{ij,nm} + LODF_{ij,rs} \times PTDF_{rs,nm}) \times NewMWtransaction_{nm}$$

All these added power flow plus the original scheduled power flow on each line cannot exceed the underlying transaction limit, which is checked by the Transmission Operator. If any one of the transaction test fails from zone n to zone m, the Transmission Operator will calculate the maximum acceptable amount of power flow that can be added under the case of the new transaction or the case combined with the loss of line *rs*.

In SEPIA, it is assumed that there are no losses in the transmission process. Real-world transmission systems will have losses and therefore, enhanced physical models with this assumption relaxed would better reflect the real situations. In addition, the $(n-0)$ and $(n-1)$ tests are basic tests for checking the security of a transmission system. More practical constraints and tests in the transmission model should be considered if modeling reliability is important.

4.1.4 Decision making and adaptation

Regarding the adaptation mechanism in SEPIA, both a Q-learning module with *Boltzmann* selection and a genetic classifier learning module are designed to guide the Generation Company agents in making decisions (Harp et al. 2000). These adaptation components are two complete and independent modules in SEPIA.

Q-Learning is an online stochastic dynamic program (Watkins and Dayan 1992). The main objective of a Q-Learning algorithm is to find a positive action for the agent to take at a particular state when lacking accurate information of the rewards of actions. As a result, the major step in a Q-Learning algorithm is to evaluate the propensities of taking what actions at what states, i.e., the (state, action) pairs. Similarly, the Q-Learning module in SEPIA tries to identify a promising action with the most rewarding result. Figure 6 outlines the structure of the Q-learning module in SEPIA, which uses the stochastic Boltzmann selection procedure in selecting actions.

The Q-Learning algorithm used by each agent in SEPIA runs as follows. First, the algorithm evaluates the reward of action a as a function $Q(a)$. Then, a stochastic selector based on the Boltzmann selection mechanism is used to choose a promising action. Usually, the higher the $Q(a)$ value, the better is the chance that action a will be selected. However, because the learning algorithm also employs the annealing mechanism, when the temperature decreases to a certain level, it will always choose the action that has the highest Q value. Moreover, the Q-Learning module in SEPIA has a self-learning capability.

In addition, SEPIA includes a *Genetic Classifier-based Learning Module*, which is shown in Fig. 7. This leaning module consists of three data sets: *Rule Set*, *Match Set*, and *Action Set*, and four separate and independent sub-modules: *Genetic Algorithm* (GA), *Matcher*, *Action Selector*, and *Credit Assignment*.

The main process is summarized as follows: (1) the classifier module contains a knowledge base represented by a set of rules; (2) each rule has a condition part that specifies an agent's current state and an action part that specifies the consequent action the agent would take; (3) the rules with certain conditions satisfied are placed into a match set by the Matcher; (4) the Action Selector uses a stochastic selector based on the Boltzmann selection mechanism to choose a rule in the Match Set and implements the selected action; (5) after the effects resulting from taking that action are cumulated and measured, a credit is assigned to the implemented rule in the action set; (6) finally, GA is used to optimize and update the rule set and the fitness of each rule is evaluated by its assigned credit.

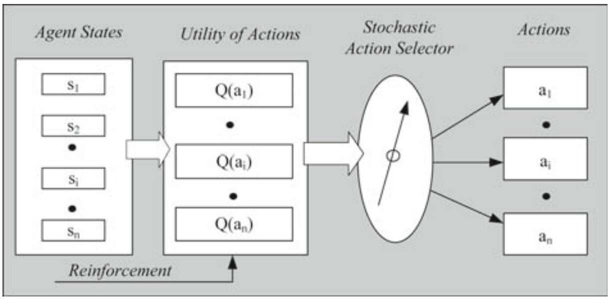

Fig. 6 The structure of the Q-Learning module in SEPIA

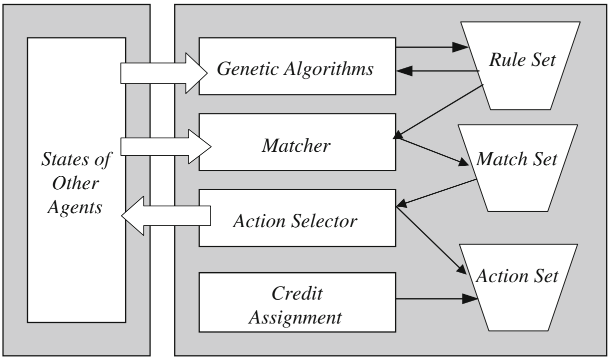

Fig. 7 The genetic classifier learning module in SEPIA

4.1.5 Features and limitations

This section summarizes the features and limitations of SEPIA. The main features of SEPIA can be summarized as follows. First, as one of the earliest ABS for EMs, SEPIA and its architecture provide a good reference for future EM ABS systems. Second, the adaptation mechanism containing both Q-learning and genetic classifier learning is a distinct feature of SEPIA. Finally, simulation models created using SEPIA have good flexibility for future extensions.

Our study reveals several limitations. First, without an ISO agent, SEPIA lacks the central operation of an EM. We suggest that an ISO agent be used when one tries to create an ABS for a deregulated EM because of the important roles that the ISO plays in a real EM. Moreover, the main functions of the ISO agent should be specified and its relationships with other agents must be defined. Second, the physical model in SEPIA does not take into account some practical issues (see Sect. 4.1.3), and therefore, practical extensions addressing these issues are suggested. Third, the adaptation mechanism in SEPIA is restricted to the Generation Companies and focuses on the bidding strategies. As an enhancement, adaptation can be extended to other decision-making levels within the Generation Companies or other types of agents.

4.2 Electricity market complex adaptive systems (EMCAS)

EMCAS (Conzelmann et al. 2004; Koritarov 2004; Conzelmann 2006) is developed by the Center for Energy, Environmental and Economic Systems Analysis at the Argonne National Lab (2007). As one of the most popular ABS systems for EMs, EMCAS has been used in several states by their local ISOs and hosted successful applications. Generally speaking, EMCAS is an ABS system with the capabilities of decentralized decision making along with learning and adaptation for agents. Each agent contains a wide range of strategies. Also, user specified market rules can be added and their impact on individual agents and the whole system could be examined.

4.2.1 Physical system structure

The *physical structure* of EMCAS is shown in Fig. 8 . It is almost the same as that of SEPIA. Each local zone in SEPIA is analogous to a *bus* in EMCAS. Similar to SEPIA, EMCAS

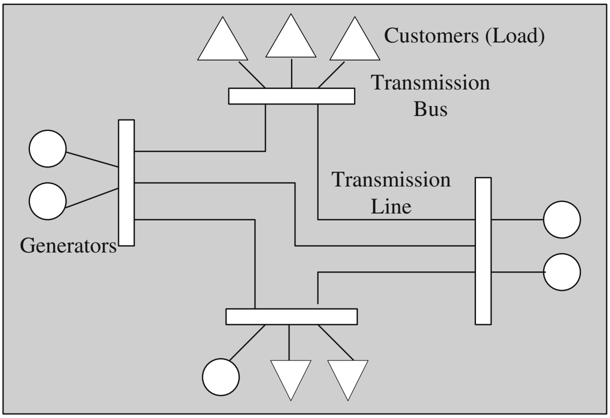

Fig. 8 Physical structure of EMCAS system (Conzelmann 2006)

assigns the local customers and generators to each bus. Customers are covered by Demand Companies and each physical generator must belong to a specific Generation Company. The two basic assumptions for the inner-zonal and inter-zonal transmission system in SEPIA are also similar in EMCAS.

However, unlike SEPIA there is no agent model of GLR in EMCAS. Also, there is no real-time transmission database like the OASIS in EMCAS. Nevertheless, the transmission as well as other information is available to all agents in EMCAS through its ISO agent. The *market information system* (MIS) which is maintained and updated by the ISO stores system level information such as system load projection, scheduled outages, historical market clearing prices, and transmission capacity. Despite some specific distinctions, the physical system structures of SEPIA and EMCAS are similar.

4.2.2 Simulation system configuration and agents

Market participants (agents) in EMCAS include Independent System Operator (ISO), Generation Company, Customer, Demand Company, Distribution Company, Transmission Company, and Regulator. The roles of these system participants in EMCAS are similar to those in SEPIA. The main difference is the additional ISO agent, which is included in EMCAS but not in SEPIA. In EMCAS, bilateral contracts could be negotiated directly between Generation Companies and Demand Companies. Alternatively, they could submit their bids to the pool market operated by the ISO. Although the Transmission Operator owns the transmission system, all transactions in the transmission system are scheduled and dispatched by the ISO. Similar to real-world operations, the main role of the Distribution Companies is to operate lower-voltage distribution systems. The Regulator is a special agent in EMCAS responsible for setting up market rules that should be obeyed by all participants in an EM.

EMCAS has a multi-layer architecture, which includes a physical layer, a business layer of bilateral contract market, a business layer of pool market, a business layer of transmission and demand companies, and a regulatory layer. The first layer—the *physical layer*—consists of physical elements in an EM like generators, transmission systems, distribution systems, and customer's loads. At this level, the ISO conducts a constrained optimal power flow (OPF) to schedule the power output of the corresponding Generation Companies to satisfy the load demands.

In the *bilateral power market layer*, the process of making direct bilateral contracts between Generation Companies and Demand Companies is similar to that of SEPIA. The difference is that SEPIA allows only bilateral contracts as a market option because it does not have an ISO or a pool market.

In the *pool market layer*, both supply and demand bids at the day-ahead level are submitted to the pool market operated by the ISO. The ISO provides public information for all the agents including past clearing prices, past load demands and the forecasted load projection using the MIS. There are two settlement options in the pool market. In the first option, the locational marginal price (LMP) is paid to all Generation Companies for selling power to the customers in a specific location. In the second market option, a Generation Company receives the same payment as the bid prices. In a pool market, the Generation Company would check with the MIS and consider its own situations before submitting bids. Moreover, for any submitted bid, the Generation Company would conduct a Unit Commitment to determine the optimal allocation of output among its generators. Simultaneously, each Demand Company submits its demand bids according to the load schedules from its customers. Finally, after collecting the supply and demand bids and considering the transmission constraints, the ISO makes the bid acceptance decision and conducts the dispatch for the next day.

In the fourth layer,*Transmission Companies* and*Distribution Companies* are the actual owners of the physical transmission system and the distribution system, respectively. Their roles are to operate and maintain their physical systems in a manner similar to the real system. The exact schedules of the system usage depend on the load schedules from the bilateral contracts or approved by the ISO.

In the last layer, the *regulator* is responsible for making and monitoring bidding rules, bilateral contract rules, and reimbursement rules in the EM. There is also an agent of special event generation, whose role is to generate contingent events such as the increase of fuel price, the change of customer loads, and generator or transmission outages. The inclusion of special events in EMCAS makes it a more realistic representation of the real power system.

4.2.3 The role of ISO in EMCAS

The ISO in EMCAS has five main functions:

(1) *Projection function*: it is responsible for forecasting system demand and available transmission capacity.
(2) *Market function*: it operates a pool spot market and calculates the market clearing price (MCP). In addition, the ISO also needs to determine locational marginal price (LMP) based on the transmission costs, congestions, and other security related requirements.
(3) *Scheduling function*: the ISO schedules each transaction in the system and approves schedules based on the bidding results of the pool market, the submitted bilateral contracts, and the available transmission capacity. It also runs the day-ahead system-level Unit Commitment and Scheduling. According to the commitment results, the ISO decides whether to accept or reject pool market bids or bilateral contracts.
(4) *Dispatching function*: the ISO dispatches generators according to load schedules in a real-time manner to meet the demand and ensure necessary security requirements.
(5) *Settlement function*: the ISO calculates payments (or receipts) among Generation Companies, Demand Companies, Transmission Companies, and Distribution Companies.

The ISO in EMCAS uses a specific module called the Argonne Load Flow (ALF) (North et al. 2002) to conduct transmission flow analysis using both AC and DC models. In particular, ALF uses Newton-Raphson and fast decoupled methods for AC power flow problems. In addition, ALF employs network reduction to reduce a large transmission network into an equivalent but much smaller one. Network reduction techniques are important for large-scale systems like EMs because of the difficulty in modeling a large network in high resolution while maintaining efficiency in computation. Furthermore, reduction methods can be used in other aspects such as reducing the number of agents in EMs. This could be a potential research topic.

4.2.4 Decision making and adaptation

Another distinct feature in EMCAS is that each Generation Company is allowed to make decisions on six levels, which are Hourly/Real-Time Dispatch, Day-ahead Planning, Week-ahead Planning, Month-ahead Planning, Year-ahead Planning, and Multi-Year ahead Planning (Veselka et al. 2002). These six levels of planning are briefly introduced in the following.

(1) *Hourly/Real-Time Dispatch*: the ISO regulates the real-time operations of the Generation Companies based on the bilateral contracts, accepted bids in the pool market, and real-time opportunistic bids.
(2) *Day-ahead Planning*: after Generation Companies make unit commitment schedules for next day, they provide offers to Demand agents for bilateral contracts. Alternatively, their supply bids can also be sent to the pool market.
(3) *Week-ahead Planning*: weekly contracts are made with individual Demand agents and are sent to the ISO for approval. There are no supply bids for the pool market at week-ahead and longer intervals. In this level, day-ahead strategies could be adjusted if necessary.
(4) *Month-ahead Planning*: monthly bilateral contracts are made up with Demand agents and sent to the ISO for approval. In this level of planning, week-ahead marketing strategies could be adjusted if necessary.
(5) *Year-ahead Planning*: beside the yearly bilateral contracts, month-ahead marketing strategies could be adjusted. Also, the maintenance of physical generators could be planned at this level.
(6) *Multi-Year-ahead Planning*: in addition to bilateral contracts, year-ahead marketing strategies could be adjusted. For example, system capacity expansions or other long-term planning can be conducted at this level.

The basic decision process in each agent is composed of several procedures. First, each agent must specify and comply with some decision rules depending on its roles. Whenever an agent makes a decision, it will consider the results of similar decision made previously (Look Back), those related to projection results (Look Ahead), and its current conditions (Look Sideways). In summary, the "*Look Back*" procedures refer to the stored information representing short- or long-term memory. Such historical information or results can be used in making the current decision. The "*Look Ahead*" procedures serve as the projection mechanism, which estimates the impact of the current decision. Finally, the "*Look Sideways*" procedures mainly consider the current situations in the underlying environments.

Adaptation in EMCAS could assist its agents to make decision. There are two forms of learning in EMCAS including observation-based leaning and exploration-based learning (North et al. 2002; Veselka et al. 2002). In *observation-based learning*, the decision for the next step mainly depends on the previous performance, while in *exploration-based learning*, the agent explores various possible strategies and then slightly adjusts the adopted strategy that expects to have a good performance in the near future. However, whenever there are big changes occurring in the environment or the current strategy has been used for a fixed length of period, the agent will re-start the new exploration process. Unlike SEPIA, there is no separate or independent adaptation module in EMCAS. The adaptation process in EMCAS is supported by pre-specified decision rules and no adaptation (self-learning mechanism) exists for such decision rules. Thus, agents in EMCAS have lower adaptation capability than those in SEPIA. Moreover, the adaptation in EMCAS is restricted to Generation Company agents.

4.2.5 Features and limitations

The main features of EMCAS can be summarized as follows:

(1) The functionalities of the ISO agent are relatively complete.
(2) It has six-temporal levels of decision making for Generation Companies.
(3) It includes special/contingent events.
(4) It allows two forms of adaptations including observation-based and exploration-based learning.

Although there are several possible limitations of EMCAS system such as no separate and self-learning adaptation and simplified physical models, EMCAS is currently regarded as one of the most comprehensive ABS systems for EMs. It models almost all important EM participants as well as their strategic behaviors and decision making. EMCAS has successful applications in several states in the USA, such as Illinois. One could refer to (or improve) some of the features in EMCAS when creating a new EM model, including the physical system structure, the definition of market participants (including ISO) and their interactions, and the decision making and adaptation process in each agent. For example, the multi-level decision framework in the Generation Companies can be extended to other agents such as Consumer Companies and Demand Companies.

4.3 Short-term electricity market simulator-real time (STEMS-RT)

4.3.1 System configuration of STEMS-RT

STEMS-RT was developed by the Electric Power Research Institute (EPRI). The major entities in STEMS-RT are the Market, Human Participants, and Computer Agents (Entriken 2005). Each human agent or computer agent represents either a buyer (Consumer or Demand Company) or a seller (Generation Company). Both Human Participants and Computer Agents interact with the Market by submitting their bids. Human participants in the Market use their own strategies, while Computer Agents employ their built-in bidding strategies.

4.3.2 Bidding process of STEMS-RT

STEMS-RT assumes that each supplier (Generation Company) will be paid by the marketing clearing price (MCP) (Audouin et al. 2006). Each bidding process in STEMS-RT runs for several rounds. In each round, an agent submits bids according to the public information from the Market and the bidding results from previous rounds. Usually, the suppliers in STEMS-RT use two bidding strategies. The first strategy is a conservative one, which is to bid all production capacity at the marginal cost. The other strategy is a greedy one, which tries to maximize the profit on a short-term basis. The consumers use only one strategy, which is to bid the willing-to-pay price.

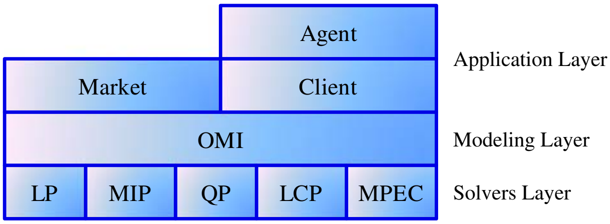

Fig. 9 Three layered STEMS-RT system architecture (Entriken 2005)

4.3.3 System architecture of STEMS-RT

The system architecture of STEMS-RT is displayed in Fig. 9. It consists of three layers: Application, Modeling, and Solvers. There are three types of applications in the Application Layer: Market application, Client application, and Agent application. The main functions in the Market application are to make decisions of accepting or rejecting bids from human or computer agents, and to solve market clearing problems. Client applications provide interfaces for human participants to submit their bids to the Market and to receive bidding acceptance results. Agent applications mainly support bidding processes of computer agents. The bidding decision of each agent in each round depends on previous MCPs and previous bidding results.

The modeling functionality is supported by the Optimization Modeling Interface (OMI) in the Modeling Layer. Models can be created at this layer to study problems on market clearing for market applications and problems on bidding strategies for agent applications. The Modeling Layer is written in Java and can create models in Linear Program (LP), Mixed Integer Program (MIP), Quadratic Program (QP), Linear Complementarity Problem (LCP), and Mathematical Program with Equilibrium Constraints (MPEC). Finally, all the mathematical models built in the Modeling Layer can be solved in the Solvers Layer, which contains third-party software for solving the models.

4.3.4 Features and limitations

The main features of STEMS-RT are summarized as follows.

(1) Agents in STEMS-RT rely on mathematical programming for bidding decisions. All decision-making problems in STEMS-RT are formulated as mathematical models. Optimization software such as MINOS (Murtagh and Saunders 1998), LINDO (Schrage 1991), or CPLEX (ILOG 2003) can be used to solve the optimization problems.
(2) The latest techniques and strategies for bidding and realistic market rules have been incorporated into automated computer agents in STEM-RT. Furthermore, new bidding strategies can be added and their effects can be tested.

With its special focus, STEMS-RT might have the following limitations for general-purpose EM models.

(1) STEMS-RT does not include some important EM participants such as Demand Companies and Transmission Operators. In particular, there is no ISO agent. The Market module is used to assume some functions of the ISO.
(2) Usage of this system is restricted to the bidding process in the pool market, while other important functionalities in EMs are not considered.
(3) There is no explicit adaptation or learning process in the decision making of each agent.

4.4 National electricity market simulation system (NEMSIM)

National Electricity Market Simulation System (NEMSIM) is a special ABS system developed particularly for the Australia National Electricity Market (NEM). The agents defined in NEMSIM include Generator Companies, Network Service Providers (NSP), Retail Companies, and the National Electricity Market Management Company (NEMMCO) (Grozev and Batten 2005; Grozev et al. 2005). The roles of the NSP and the Retail Companies resemble that of the Transmission Operator and the Demand Companies in EMCAS, respectively. NEMSIM also makes several assumptions similar to those in EMCAS. First, bidding and bilateral contracts are two marketing options. The pool market of NEMSIM is also at the day-ahead level and for any longer term transactions, bilateral contracts will be used instead. Its transmission system has transmission capacity for transactions between two different regions. One role of the NEMMCO is to dispatch power from Generator Companies to meet the load demand at half-hour intervals. In the following, two common features in NEMSIM are introduced: (1) physical system configuration and (2) decision making of agents.

Physical System Configuration: NEMSIM's physical system consists of generating units, generating plants, inter-connectors, and transmission lines. Each physical element has its own technical or operational attributes.

Decision Making of Agents: each agent defined in NEMSIM is an independent unit with adaptation and learning capabilities. The decision making of each agent is motivated by its goals but could be affected by behaviors of other agents or any related environmental changes in EMs. Among all decisions, the study of bidding strategies in the pool market or bilateral contract market is emphasized in NEMSIM. NEMSIM also adopts a six-temporal-level decision making similar to that of EMCAS (i.e., hourly/half hourly, daily, weekly, monthly, yearly, and multi-yearly). The adaptation mechanism in NEMSIM is currently based on the *look-ahead* decision process. Simulations are used in NEMSIM to test or compare various possible strategies. Those strategies that lead to the best results are then chosen by the agents.

The main features of NEMSIM are summarized as follows.

(1) NEMSIM considers all the important system participants in EMs. Most of the behaviors of each individual agent are also modeled.
(2) More than 6 years of historical data are used in NEMSIM to drive the simulations. Thus, its validity depends on how accurate the historical data represent the real demand and contingent events. For example, if some extreme events happen in about every 10 years, then the 6-year-based demand model might need modifications to account for these events unobservable in the data.
(3) Different from other ABS systems, functions of the pool market in NEMSIM can be extended to the bilateral contract market.
(4) One objective of NEMSIM is to investigate and compare the effects of new scenarios such as new plants, maintenance, new market rules, and special events, which might be a solution to the problem discussed in (2).
(5) Some environmental issues such as the estimation of greenhouse gas emission are studied in NEMSIM.
(6) The studies in NEMSIM cover short-term trading, the medium-term contract market, long-term investment, the estimation of greenhouse gas emission, and the study of new scenarios.

However, because NEMSIM is designed particularly for the Australia NEM, its extensions to other EMs may be difficult and could require significant modifications. Moreover, it lacks the function for transmission analysis. Future development of NEMSIM might add learning algorithms such as genetic algorithms, genetic programming, Q-learning, or classifier systems into the adaptive decision process.

4.5 Other agent-based simulation in electricity market

This section reviews several ABS packages in EMs developed for research purposes and reported in the literature. These ABS packages have received a significant amount of attention in the literature. More important, the framework of each ABS package contains relatively complete functionality and common features for EMs.

Bagnall and Smith (2005) use an ABS model to study the EM in the United Kingdom (UK). The motivation of that study is to simulate learning behavior toward optimal strategies of adaptive agents, and to understand the effects of market mechanisms on bidding strategies of generating companies. In the simulation model, the generating companies own several generators characterized by various fuel types and cost profiles. Each generating company prepares a daily supply bid for each generator. Unconstrained or constrained unit commitment can be solved at this level. Based on the obtained unconstrained or constrained schedules, settlement software is used to calculate various prices such as *System Marginal Price* (SMP), *Pool Purchase Price* (PPP), and *Pool Selling Price* (PSP). The simulation objective is limited to the study of the behavior of generating companies. The roles of the ISO, however, are not considered. More important, the simulated market represents the UK EM before the implementation of the New Electricity Trade Arrangement (NETA). NETA is a regulation proposed in 2001 for the EM of England and Wales with the aim of replacing the pool market with bilateral trading. Substantial modifications are needed to accurately represent the current UK EM.

Bower and Bunn (1999) conduct a comparison between a day-ahead pool market and a bilateral contract market using ABS models. The simulated market represents the EM after the implementation of the NETA in 2001. The underlying research motivation is to study the effects of transforming the England and Wales EM from a day-ahead pool market to a bilateral contract market.

In their simulation model, each generating plant is modeled as an agent with distinct attributes including capacity, fuel type, efficiency, availability, and so on. Four auction models are studied in the simulation that allows combinations of two market types, two bidding periods, and two settlement systems. The first auction model is a day-ahead pool market with daily bidding and uniform prices (SMP payment). The second one is a day-ahead pool market with daily bidding period and discriminatory payment (bid price payment). The third one is a bilateral short-term market with hourly bidding and uniform prices. The final one is a bilateral short-term market with hourly bidding and discriminatory price. An ABS model is built for each of these four auction models and the resulted MCPs are compared. Results from the simulations show that the lowest price was achieved in the auction model of a day-ahead pool market with daily bidding and SMP payment. The effects of these two factors (bidding period and settlement) are compared.

In summary, their ABS models mainly study different auction models in an EM. Although it does not model complete functionalities of an EM and the system participants are restricted to generating plants, their investigation of suitable auction models is a distinct feature that does not commonly exist in other EM ABSs. Therefore, this feature should be considered as an optional function of the ISO when developing a new ABS model for EMs.

Sun and Tesfatsion (2006, 2007) propose an open-source agent-based framework called the Agent-based Modeling of Electricity System (AMES), which has four main components: traders, transmission grids, markets, and an ISO. AMES is programmed in Java and developed using *Repast for Java* (Repast Homepage 2007). The trader agent contains two types of entities: buyers (load serving entities) and sellers (generators). The market component has a two-settlement system, which consists of a day-ahead market and a real-time market. The ISO has four functions: system reliability assessment, day-ahead unit commitment, dispatch, and settlement. A reinforcement learning module, called *JreLM*, is integrated into the simulation framework for adaptive decision making of traders. The physical transmission system is modeled as a five-node transmission grid. In summary, AMES is composed of several separate modules, each of which could be extended, and new modules could also be added. Also, AMES is open source. All these features facilitate the future extensions of AMES.

Praça et al. (2003a,b) develop the Multi-Agent System that Simulates Competitive Electricity Markets (MASCEM) to study competitive electricity markets. The agents in MASCEM include a market facilitator, generators, consumers, market operators, traders, and a network operator. The markets considered in MASCEM are a pool market and a bilateral contract market. The trader agents are similar to the Demand Companies in EMCAS. Consumers in MASCEM are not necessarily assigned to a trader. Instead, individual consumers could directly submit their buy bids to the market operator in the pool market. The market facilitator, mainly acting as a regulatory agent, is employed to coordinate and monitor the simulated EM. The market operator assumes some ISO administration functions such as calling for bidding, receiving sell and buy bids from generators and consumers (or traders), respectively, determining market clearing prices (MCP), and finally deciding to accept or reject the received bids. In the bilateral market, generators and traders directly negotiate with each other to make bilateral contracts. However, both the accepted bids in the pool market and bilateral contracts must be sent to the network operator to check the transmission capacity. Adaptation in the form of dynamic strategies and scenario analysis is utilized by the supply and demand agents to help their bidding decisions.

In summary, the system configuration and functionality of MASCEM are similar to EMCAS. A distinct feature in MASCEM is scenario analyses. Supported by historical information, scenario analyses conducted by each agent could cover the strategic decisions in both markets by analyzing possible scenarios and determining the best strategy under each scenario.

Veit et al. (2006) use ABS to study the dynamics of a two-settlement EM consisting of one forward market and one spot market. In their ABS models, demand agents, supply agents, transmission line provider agents (TLP), and an ISO are the principal system participants. The forward market and spot market are maintained and operated by the ISO. In the forward market, forward demand and supply bids are submitted to the ISO, who also calculates the forward prices. In the spot market, after receiving spot demand and supply bids, the ISO solves the spot allocation problem modeled as a mixed linear complementarity problem (MLCP) and calculates the spot prices. The ISO is an administrative agent, who maintains the functions of market, dispatch, and settlement. The decision making of the ISO and generating companies are the foci of the study. First, the dispatch decision conducted by the ISO is modeled as MLCPs and solved using nonlinear programming (NLP) techniques. Second, a generating company must determine the output of its generators in the forward and spot markets with the objective of maximizing its profit, which is also modeled as an MLCP. By combining these two decisions problems in a two-settlement market, the overall decision making including the allocation of power output for the forward market and the spot market for each generating company, and the dispatch schedule made by the ISO, is formulated as an equilibrium problem with equilibrium constraints (EPEC). Instead of using mathematical programming techniques, the authors used ABS to obtain the optimal decision for each entity in the problem. The strategy of modeling decision making and solving them mathematically is similar to that of STEMS-RT.

Weidlich et al. (2004) develop an agent-based computational economics (ACE) tool called PowerACE to study the CO_2 emission trading market. Agents defined in PowerACE are generators, load serving entities, electricity traders, long-term planners, market operators, certificate traders, and consumers. The ABS model is developed based on Java using *Repast*. Besides the usual trading in both the pool and bilateral markets, one distinct feature in PowerACE is the proposal of a market for CO_2 emission allowance. CO_2 allowance trading agents are the main participants in this market. A typical bid for CO_2 emission allowance consists of the type of bidding (buy/sell), bidding price, bidding quantity, and valid period. The ABS model investigates the effects of CO_2 emission trading on the bidding prices in regular power markets as well as the long-term investment decision. The capability of investigating environmental issues (such as CO_2 emission) is a good optional feature to be included in the development of new EM ABSs because these issues, besides receiving increasing popular attention, could change the power production structure and long-term investment decisions of generation companies.

5 Analyses and comparisons of common elements

This section conducts an analysis and comparison among all the reviewed ABS packages in EMs. Basic and common elements of ABS in EMs are distilled from existing systems and the literature. These elements are system participants, the ISO and its main functions, system capabilities, electricity market models, transmission models, and decision making and adaptation for each type of agents. Table 1 summarizes the analyses of all the reviewed ABS packages in EMs under these elements.

5.1 System participants

In general, each EM participant is modeled as an agent in the ABS model. Each participant is responsible for some EM functionalities and has a specific decision making framework with possible adaptation mechanisms. The agent model of an EM participant is a fundamental and critical component because it has a direct impact on other elements in the EM. Once a particular system participant in an EM is neglected, all the related design issues and capability in the ABS model will not be included. Thus, the completeness of major participants is a crucial measurement of the functionality of the ABS model. In general, all major participants in an EM should be modeled as agents. Exceptions exist for those ABS models studying special issues that require necessary simplifications. Based on the summary given in Table 1, the major participants for a relatively complete EM model include generators, generation companies, customers, customer companies, transmission systems, transmission companies, and the ISO.

In SEPIA, all the aforementioned system participants except the ISO are modeled. In addition, the GLR in SEPIA is a special agent that does not commonly exist in other EM ABSs. The system participants and agent model with an ISO and two additional agents (the regulator and distribution companies) in EMCAS are relatively complete. STEMS-RT focuses on the bidding behaviors of agents in the pool market and therefore, only generation companies and demand companies are modeled. Similar to EMCAS, the system participants in NEMSIM are also relatively complete. The NEMMCO, the NSP, and the retail company in NEMSIM

Table 1 Comparisons of the common Elements in ABS EM Systems

Systems	SEPIA	EMCAS	STEMS-RT	NEMSIM	Bagnall's	Bower and Bunn's	AMES	MASCEM	Veit et al.	PowerACE
Elements										
System participant	Customers, customer companies, generators, generation companies, transmission operator, GLR	ISO, regulator, customer, demand companies, generator, generation companies, transmission operator, distribution companies	Customers, generation companies	NEM-MCO, customers, generator companies, network service provider, retail companies	Generator, generation companies	Generating plant	Trader, market, transmission grid, ISO	Generator, consumer, trader, market facilitator, market operator, network operator	Demand and supply agents, transmission line provider (TLP), ISO	Consumer, load serving entities, generator, electricity trader, market operator
ISO	None	Five main functions	None	Market, dispatch scheduling	None	None	Four core functions	Two core functions	Three core functions	Only market functions
System capabilities	Incomplete	Relatively complete	Market function only	Relatively complete	Relatively complete	Market	Relatively complete	Relatively complete	Relatively complete	Relatively complete
Market models	Bilateral contract	Pool market and bilateral contract	Pool market	Pool market, bilateral contract	EPM before NETA	EPM after NETA	Two settlement	Two settlement	Two settlement	Two settlement and CO_2 emission
Transmission	AC and DC	AC and DC	AC and DC	None	None	None	DC	N/A	None	None
Decision making	Bidding price only	Six levels of planning	Bidding strategies	Six levels of planning	Basic	Basic	Basic	Basic	Basic	Basic

Table 1 continued

Systems	SEPIA	EMCAS	STEMS-RT	NEMSIM	Bagnall's	Bower and Bunn's	AMES	MASCEM	Veit et al.	PowerACE
Adaptation	Q-Learning and Genetic Classifier	Observation-based learning exploration-based learning	N/A	Look-ahead decision process	None	None	JreLM	Dynamic strategy, scenario analysis	None	None

are similar to, respectively, the ISO, the transmission operator, and the demand company in EMCAS.

Bagnall and Smith (2005) and Bower and Bunn (1999) models mainly investigate the bidding process of the electricity power suppliers, and therefore, only generators and generation companies/generating plants are considered. Both AMES and MASCEM contain almost all the important participants. A trader in AMES represents either a customer company or a generation company. The market facilitator and the market operator in MASCEM act, respectively, as the regulator and the ISO in an EM. Veit et al. (2006) model considers the core agents in an EM. The demand and supply agents are actually customers and generation companies, respectively. The TLP acts as the transmission operator. Finally, besides the core agents, PowerACE also includes two special agents: the long-term planner and the certificate trader. The certificate trader is responsible for all the transactions in the CO_2 emission market.

5.2 The ISO and its main functions

Due to the special characteristics of electricity power as a commercial product and the tendency of deregulation in EMs, more and more EMs have started to employ a central administration. As a result, the importance of an ISO has been recognized.

In EMCAS, the relatively complete functions of the ISO including projection, marketing, scheduling, dispatch, and settlement, are the reference used in evaluating the ISO functions of other ABS models. For a particular function, small differences may exist among ABS models, but the basic functionalities are similar. In summary, NEMMCO (i.e., the ISO in NEMSIM) has three core functions: marketing, scheduling, and dispatch. SEPIA does not model the ISO and the related functions are shared among generation companies, customer companies, and a transmission operator. For example, the marketing function is fulfilled by generation companies and customer companies in the form of bilateral contracts. The settlement function is conducted by the transmission operator because it determines the actual transmission schedules. STEMS-RT does not consider the participation of an ISO, but its market module assumes the marketing functions of the ISO. Other ABS models without ISO include Bagnall and Smith (2005) model and Bower and Bunn (1999) model. The ISO in AMES maintains four functions: forecast, scheduling, dispatch, and settlement. It calculates locational marginal prices (LMP) and conducts hourly balancing commitment and dispatch under the approximate DC optimal power flow (OPF). The ISO in MASCEM only takes the marketing and scheduling functions, and the dispatch task is fulfilled by the network operator. In Veit et al. (2006), the ISO has core functions such as marketing, scheduling, and dispatch. In PowerACE, a similar agent called market operator assumes only the marketing function of the ISO.

5.3 System capabilities

In general, the principal system capabilities of EMs consist of generation, marketing, transmission, distribution, and central administration. Usually, the distribution system is omitted in many EM ABS systems.

SEPIA maintains three capabilities including generation, marketing, and transmission, but lacks the role of central administration. EMCAS is one of the most complete ABS systems for EMs because it maintains all these five capabilities. In addition, EMCAS is capable of simulating the impacts of special events. The capabilities of STEMS-RT are restricted to the bidding functions in the pool markets. The capabilities of NEMSIM include generation, marketing, and central administration by NEMMCO. Because NEMSIM assumes unlimited transmission capacity, transmission analyses are not included. Bagnall and Smith (2005) model only contains partial capabilities of generation, marketing, and dispatch because all these capabilities are completely controlled by the generation company agents. Bower and Bunn (1999) model mainly focuses on the market function and leaves out other system capabilities. Common system capabilities in AMES, MASCEM, Veit et al. (2006) model, and PowerACE cover generation, marketing, transmission, and some central administrative functions. In particular, a five-node transmission grid is used in AMES as a simplified physical transmission model. PowerACE maintains additional capability for studying the environmental issues and an additional market for CO_2 emission is constructed to investigate its effects on regular markets.

5.4 Transmission models

Transmission analysis is an important and practical issue in this topic. Many EM ABS models ignore this issue. Transmission analysis in SEPIA considers both AC and DC models, and $(n-0)$ and $(n-1)$ tests are used to check the security of the transmission capacity. EMCAS uses its ALF module to conduct both AC and DC transmission load analyses. Network reduction techniques are also employed in EMCAS to reduce model complexity to facilitate transmission analyses. In contrast, the ABS model in STEMS-RT neglects the transmission capabilities. Thus, no transmission models or analyses are considered. The same issue applies to both Bagnall and Smith (2005) and Bower and Bunn (1999) models. In AMES, a DC model is used to dispatch the scheduled electricity transmission. Similar to SEPIA, MASCEM uses a network operator agent to conduct transmission analyses. However, we could not find the details regarding its transmission model. In other reviewed ABS models, transmission analyses are not considered.

5.5 Market models

Market models depend on the problems to be studied or their underlying EMs. In SEPIA, the market model only includes bilateral contracts as marketing option, while in EMCAS, the market model has two market choices: pool market bids and bilateral contracts. The market models of NEMSIM are similar to that of EMCAS. STEMS-RT only considers the pool market. Bagnall and Smith (2005) model studies the EM in UK before the implementation of NETA, while Bower and Bunn (1999) model focuses on the UK EM after NETA. AMES uses a two-settlement market consisting of a day-ahead market and a real-time market. The EM in MASCEM includes a pool market and a bilateral contract market. Veit et al. (2006) model has a two-settlement EM, which is composed of one forward market and one spot market. Finally, in PowerACE, in addition to two regular markets (a pool market and a bilateral market), an additional market for CO_2 emission allowance is included.

5.6 Decision making and adaptation

Decision making for each agent is a basic element in ABS for EMs. It is directly related to the capabilities and functionalities of the corresponding agents. The six-temporal-level decision-making framework of EMCAS and NEMSIM is a distinct feature. In SEPIA, the decision making is restricted to the bidding prices. Similarly, the main decisions for each agent in STEMS-RT are bidding strategies in the bidding process. In other ABS models, each agent only makes the basic decision directly related to its specific roles.

Another issue is the adaptation mechanism, which is a way for agents to mimic the process of decision making observed in the real world. While adaptation is *not* a necessary feature for agents to perform certain tasks, which has been shown in the literature of artificial intelligence, this mechanism is critical for ABS models of EMs because the agents in EM ABS models are metaphors of human and are expected to mimic certain behavior of actual human by using learning and adaptation. In SEPIA, adaptation is emphasized and there are two separate and independent learning modules: the Q-learning and the genetic classifier learning. Adaptation in EMCAS is somewhat simpler than that of SEPIA, but it still contains two forms of learning: observation-based leaning and exploration-based learning. The decision making in STEMS-RT is based on experience and no explicit adaptation module can be found. The adaptation capability in NEMSIM is in the development stage and is currently implemented by a look-ahead decision process. More advanced adaptation modules are expected in future development. Bagnall and Smith (2005) model and Bower and Bunn (1999) model do not explicitly define the adaptation in the agents' decision making. In AMES, the module of *JreLM*, which is equipped with reinforcement learning methods, is used to guide the trader agent to make bidding decisions. Similarly, adaptation in MASCEM is conducted in the bidding process for both supply and demand agents. The specific learning methods used in MASCEM are dynamic strategies and scenario analyses. In Veit et al. (2006) model, the decisions for generation companies and the ISO are formulated and solved mathematically; thus, dynamic adaptation is not considered explicitly. Lastly, adaptation mechanism is also not explicitly defined in PowerACE.

6 A framework of ABS in EMs

This section presents a succinct, yet representative, EM ABS framework, which is built upon some of the features in the reviewed ABS systems. Considering the fact that each EM has its own characteristics, this ABS framework would only address essential design issues and functionalities for the EMs. The common design issues used to construct this ABS framework are physical transmission system configuration, the definition of agents and their interactions, the roles of the ISO, the electricity market model, and the decision making and adaptation in each agent. Each issue is described separately in the following sections.

6.1 Physical system and configuration

Ideally, an EM ABS model considering practical power transmission should include a physical transmission model. The structure of the physical transmission system in SEPIA and EMCAS represents common situations in most real-world EMs. AMES uses a similar but simplified five-node transmission grid as the physical system model. The physical system of the ABS framework builds on these physical systems. It includes three common physical components: generators, customers (loads), and transmission lines (systems). Similar to SEPIA and EMCAS, in the ABS framework, each local region is represented by a single bus. There are several generators and customers located at each local region, which are attached to the represented bus for that region. Any transaction between two regions is conducted by the physical transmission system. To reduce the complexity, the distribution system in the physical transmission model is not included. Thus, the transmission system links generators from one region to customers in another region. Like most other approaches, two common specifications are made here. First, there is no transmission within the same region. Second, for any transmission between two local regions, the capacity and other basic security tests

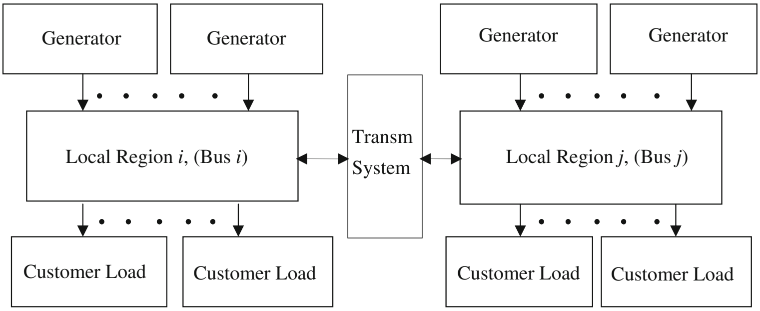

Fig. 10 Basic unit of physical system Structure

should be monitored. This physical transmission structure is presented in Fig. 10. Observe that the two local regions are connected by the transmission system. Although other extensions can be considered, this concise model has captured most of the common features in an EM.

The exact physical models for system participants such as the load model of customers, the cost model of generators, and the physical transmission model are EM dependent. Nevertheless, it is suggested that both AC and DC models should be considered when performing transmission analyses. Besides capacity limitation, other practical constraints can be considered as well if needed.

6.2 Agents and their interactions

Agents recommended in this ABS framework include an ISO, Generators, Generation Companies, Customers, Customer Companies, and Transmission Companies. To define these agents, we shall specify for each type of agent the roles, objectives, and interactions with other agents in the following.

Each generation company could own several physical generators. Each generator belongs to a generation company. Three basic attributes characterizing a generator include fuel type, production cost, and generating capacity. Each of these attributes could influence the generator company's production schedules and bidding strategies. The physical model of generators is supported by historical data and current information (situations). The only role of generators is as simple as generating electricity in accordance with the production schedule determined by its generation company. In determining the production schedules, each generation company will consider the physical characteristics and technical constraints of its generators. The roles of generation companies are production and energy sales. First, generation companies submit bids to the day-ahead pool market or make bilateral contracts with customer companies. Then, production schedules are made based on the final bidding results. Before making any decision, the generation companies usually consult the system level information from the MIS.

Individual customer has no strategic behaviors and decisions. Instead, such strategic behavior existing in a real market has been shifted to the customer companies that serve as the "agents" seeking lower price electricity service for customers. Customers only interact with their customer companies by providing their load demands and making payments for the purchased electricity. Finally, the transmission companies own the transmission systems but all transmission schedules are determined and approved by the ISO. The only operation of a transmission company is to implement the transmission schedules. Also, for simplicity, there is no strategic behavior or decisions for both the transmission system and the transmission operator.

The ISO still serves as an administrative coordinator for the whole EM. It is an independent entity in that it neither has direct control over other agents, nor does it represent the benefits of any particular type of agents. The ISO's objectives are to manage and monitor the EM to ensure its normal operations.

Several main functions of the ISO are defined in this framework. First, the ISO has the projection function, which is not limited to the estimation of customer demand or generation capacity, but also predicts the behavior of important market participants especially generation companies and customer companies. Using the prediction results, the ISO can identify potential problems in the EM and execute system-level regulations if necessary.

Second, the ISO assumes the energy sale function in the EM. A two-settlement market is considered in this framework including a day-ahead pool market and a bilateral contract market. Both markets are maintained and operated by the ISO. Resembling other EM ABS systems, generation companies and customer companies in this framework also submit day-ahead bids to the pool market. Alternatively, these two types of agents could directly make longer term bilateral contracts (up to year-ahead level). To fulfill its marketing function, the ISO also maintains an MIS to provide information that would assist the bidding decisions of customer companies and generation companies. Public information stored in the MIS includes forecasted load, system capacity, and transmission information. Especially, the detailed real-time transmission data provided in the MIS is similar to that given in the OASIS in SEPIA. Therefore, the MIS in this framework takes the roles of EMCAS's information system and SEPIA's OASIS.

Third, the ISO performs the scheduling function as in EMCAS, NEMSIM and AMES. All transactions in the two markets must be approved by the ISO. After receiving buy (or sell) bids from customer companies (or generation companies), the ISO makes the acceptance decision for each submitted bid. Two constraints must be considered: (1) all the customer demands must be satisfied; and (2) the transmission capacity and practical technical constraints must be met.

Finally, the ISO conducts the dispatch procedures. Compared with other EM ABS systems, this framework maximizes the central administration role of the ISO. Figure 11 illustrates the interactions among principal market participants (agents) and their roles in this framework.

In Fig. 11, generation companies interact with the ISO by submitting bids to the pool market, receiving bidding results, and conducting dispatch specified by the ISO. In addition, although the generation companies could directly negotiate with the customer companies for long-term bilateral contracts, these contracts should be approved by the ISO. The interactions between customer companies and the ISO are similar. The objective of customer companies is to reduce the amount of payment to the generation companies and transmission companies. Finally, the transmission companies deliver transmission information to the MIS and implement the transmission schedules determined by the ISO. At the physical system level, transmission lines transmit electricity directly from generators to customers, as demonstrated in Fig. 11. Agents of Distribution System and Distribution Companies are not considered in this framework due to their simplistic roles, but could be added for specific EMs if necessary.

6.3 Decision making and adaptation

This framework includes three types of market participants with strategic decision making: the ISO, generation companies, and customer companies. The decision-making procedure for generation companies and the ISO are shown in Figs. 12 and 13, respectively. Both procedures include two types of decisions: Short-Term Operational Decisions and Long-Term Planning.

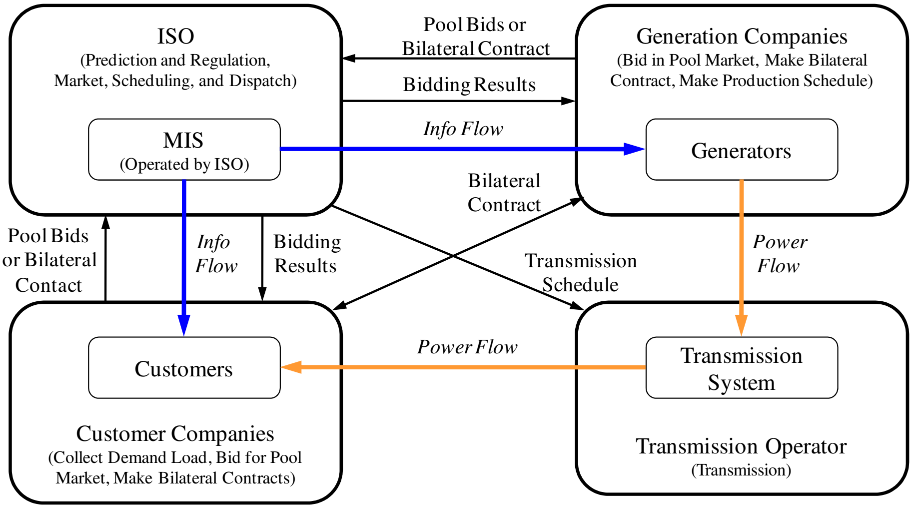

Fig. 11 Interactions among agents in the ABS framework

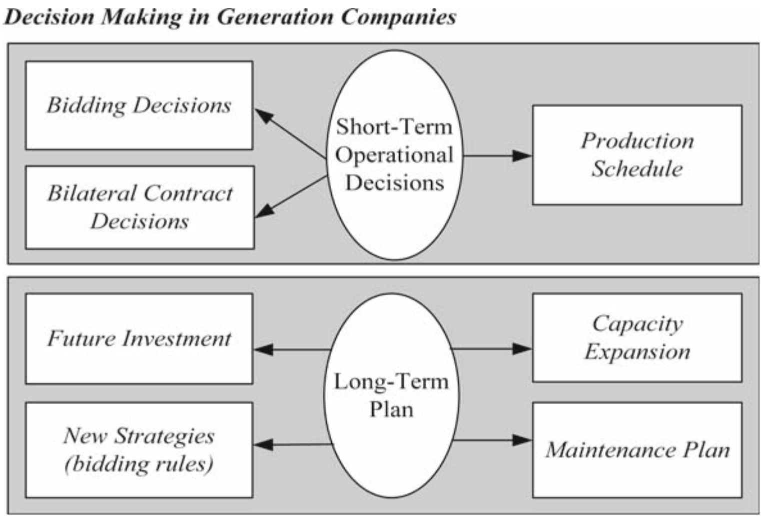

Fig. 12 Two-level decision making in generation companies

Short-Term Operational Decisions in Generation Companies include: (1) bidding decisions in day-ahead pool market, (2) decisions in bilateral contracts, and (3) daily schedule of electricity power production. All these regular operational decisions are one of the roles of Generation Companies. It is worth mentioning that the bidding decisions of Generation Companies also depend on the market model. *Long-Term Planning* in Generation Companies include: (1) maintenance plan, (2) capacity expansion of generators, (3) investment of new generating plants or production techniques, and (4) tests of new bidding strategies or regulation rules. These long-term plans, which are similar to those in EMCAS, NEMSIM, and PowerACE, are optional and depend on specific applications. It should be pointed out that there are explicit or implicit influences among different decisions. For instance, the

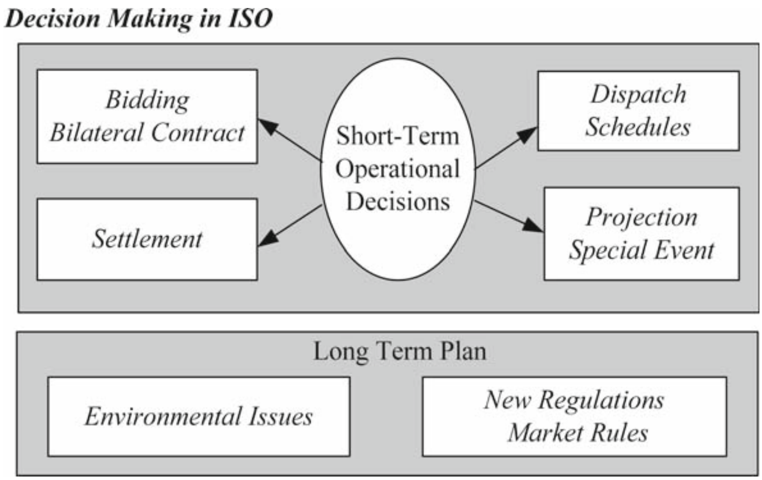

Fig. 13 Two-level decision making framework of ISO

decisions on the pool biddings or bilateral contracts could affect the production schedules; and long-term plans could be driven by short-term behavior and vice versa.

The decision making of the ISO is tied to its functions. *Short-term operational decisions of the ISO* include: (1) acceptance decisions for submitted bids in the pool market, (2) acceptance decisions for bilateral contracts, (3) transmission dispatch decisions, (4) settlement for each entity, and (5) system-level regulations. All the regular operational decisions of the ISO are recommended and included in this framework because they are common in many real-world EMs. The decisions made by the ISO in EMCAS, NEMSIM, AMES, MASCEM, and Veit et al. (2006) model represent the most common decisions in a typical EM. Typically,*long-term planning of the ISO* is optional and could include designing and setting new regulations or market rules, and managing various environmental issues.

Adaptation Mechanism in decision making is emphasized in this ABS framework. As in most existing EM ABS packages, the adaptation mechanism is mainly applied to the bidding process of Generation Companies and/or Customer Companies. Choices of learning algorithms include genetic algorithms, genetic programming (GP), genetic classifier, Q-learning, and Roth/Erv learning (Roth and Erev 1994; Erev and Roth 1998). Most of these algorithms have been applied to different EM ABS models. Specific descriptions of the learning algorithms and adaptation modules are out of the scope of this ABS framework and would also depend on specific applications. A detailed study on learning algorithms applied to market participants can be found in Weidlich and Veit (2008). For simplicity, there is no adaptation in the ISO's decision making in this ABS framework. Finally, decision making of Customer Companies is restricted to bidding decisions in the pool market. Similar adaptation techniques can be applied to Customer Companies.

6.4 Summary of ABS frameworks for EMs

An ABS framework is outlined based on the reviewed packages and literature. Several common elements and design issues in EMs are suggested in the framework. First, the market participants cover the most common and important ones in an EM. Second, the independent administrative role of the ISO is emphasized and advocated. Third, although its system capabilities can be expanded, current functionalities have covered generation, marketing, transmission, and central administration. Fourth, the market model in this framework includes two components: a day-ahead pool market and a bilateral contact market, which are representative markets for real-world EMs. Fifth, the transmission analysis adopts both AC and DC models and considers practical security and technical transmission constraints. Sixth, the decision making in Generation Companies and the ISO is composed of two types of decisions: short-term operational decisions and long-term planning. All typical decisions of important agents are suggested according to the specific roles of each agent. Finally, this framework suggests adaptation within the decision making of agents. However, specific adaptation modules and leaning techniques are not specified and should be decided based on the underlying applications/systems.

7 Conclusions and future work

7.1 Conclusions

First, an overview of EMs is presented and a review of general ABS methods follows. The basic features of agent are summarized and the main advantages of ABS over traditional DES are presented. It is concluded that due to the complexity of EMs, ABS is a suitable tool to modeling EMs for both research purposes and commercial applications. Second, this paper reviews several existing ABS packages for EMs. SEPIA is regarded as one of the earliest ABS packages for EMs and EMCAS is considered as one of the most powerful ABS packages for EMs. The frameworks of these two systems, their components, and their study issues provide some guidelines for developing new EM ABS models. STEMS-RT, NEMSIM, and several EM ABS systems are also examined and their main features and limitations are discussed. Comparisons of all the reviewed EM ABS systems are given in Table 1. It is found that the common and important issues in EMs are physical system structure, models of physical components, the definition of agents and their interactions, and decision making and adaptation for each type of agents. These findings have led to an ABS framework for EMs presented in Sect. 6.

7.2 Future work

By abstracting the important elements and functionalities from existing EM ABS systems, a succinct yet representative EM ABS framework is constructed. It contains common components and basic functionalities of an EM. Important agents in an EM are defined and their interactions are described. Further extensions of this ABS framework should focus on its fidelity in mimicking a real market and the model size and complexity. One difficulty in modeling and analyzing EMs is their high degree of complexity, which can contain thousands of transmission lines and hundreds of generators. Therefore, reduction methods are needed to maintain a reasonable size of the model and the computational efficiency of the simulation experiments at the cost of lower fidelity. Furthermore, due to the adaptive nature of market participants in a real-world EM, adaptation mechanism should be considered in EM ABS models and different mechanisms should be tested to evaluate their performance in mimicking behavior of real-world market participants. Therefore, the study of learning algorithms is a potential research topic.

Another line of research is the use of mathematical programming in modeling and solving decision problems arising in EM analyses. This has been studied in STEMS-RT but is restricted to the bidding process. Sensitivity analysis is also a potential research area because it could reduce the number of experiments required in analyzing (or optimizing) various market settings and scenarios, which might require a large number of experiments using a trial-and-error approach due to the combinations of these settings and scenarios.

Finally, because AL and SI are related to ABS, the study of these two topics might provide insights into important issues concerning EM ABS models such as the interactions among agents, especially the bidding process in EMs.

Acknowledgments Some of the previous work of this paper was done with the assistance of Haibing Gao. This research is partially funded by the NYISO through grant PO# 7623.

References

Amin M (2003) North America's electricity infrastructure: are we ready for more perfect storms? IEEE Secur Priv Mag 1(5): 19–25. doi:10.1109/MSECP.2003.1236231
Argonne National Laboratory (2007) http://www.dis.anl.gov/exp/cas/index.html. Cited 1 Aug 2007
Audouin R, Hermon F, Entriken R (2006) Extending a spot market multi-agent simulator to model investment decisions. Proceedings of 2006 IEEE Power Systems Conference and Exposition, pp 1190–1197
Bagnall AJ, Smith GD (2005) A multiagent model of the UK market in electricity generation. IEEE Trans Evol Comput 9(5): 522–536. doi:10.1109/TEVC.2005.850264
Bonabeau EA, Dorigo MA, Theraulaz GA (1999) Swarm intelligence: from natural to artificial systems. Oxford University Press, New York
Borshchev A, Karpov Y, Kharitonov V (2002) Distributed simulation of hybrid systems with anylogic and HLA. In: the 6th International Conference on Parallel Computing Technologies, vol 18(6). Elsevier Science B.V, Amsterdam, pp 829–839
Borshchev A (2005) System dynamics and applied agent based modeling. Workshop: Agent Based Modeling: Why Bother? Presented at the International System Dynamics Conference, Boston, July 2005
Boudriga N, Obaidat MS (2004) Intelligent agents on the web: a review. IEEE Comput Sci Eng 6(4):35–42
Bower J, Bunn D (1999) A model-based comparison of pool and bilateral market mechanisms for electricity trading, energy markets group, London business school. www.caiso.com/docs/2000/11/22/2000112212555313344.pdf. Cited 1 Aug 2007
Castle CJE, Crooks AT (2006) Principles and concepts of agent-based modeling for developing geospatial simulations. UCL, Working Papers Series, Paper 110
Coensys Inc (2007) http://www.coensys.com/anylogic_applications.htm. Cited 1 Aug 2007
Conzelmann G, North MJ, Boyd G, Cirillo R, Koritarov V, Macal CM, Thimmapuram P, Veselka T (2004) Simulating strategic market behavior using an agent-based modeling approach–results of a power market analysis for the midwestern United States. In: the Proceedings of the 6th IAEE European Energy Conference on Modeling in Energy Economics and Policy. Zurich
Conzelmann G (2006) Electricity markets complex adaptive systems (EMCAS) model–a new long-term power market forecasting tool. http://www.dis.anl.gov/ceeesa/documents/emcas_overview_present.pdf. Cited 1 Aug 2007
Davidsson P (2001) Multi-agent based simulation: beyond social simulation. In: The Proceedings of 2001 International Workshop on Multi-Agent Based Simulation, pp 97–107
Entriken R (2005) Using automated agents with probe: interface requirements specification. Technical Report 2005. 1012157. EPRI, Palo Alto
Epstein JM, Axtell R (1996) Growing artificial societies: social science from the bottom up. The Brookings Institution, Washington, DC
Erev I, Roth AE (1998) Predicting how people play games: reinforcement learning in experimental games with unique, mixed strategy equilibria. Am Econ Rev 88(4):848
FERC (2006) United States of America electricity energy market competition task force and the federal energy regulatory commission, government report. Federal Energy Regulatory Commission
Finin T, Fritzson R, McKay D, McEntire R (1994) KQML as an agent communication language. Proceedings of the third international conference on information and knowledge management, pp 456–463
FIPA (1997) FIPA 97 specification part 2: agent communication language. Technical report, FIPA—Foundation for Intelligent Physical Agents
George Mason University (2007) http://socialcomplexity.gmu.edu/index.php. Accessed Cited 1 Aug 2007

Goldman C, Lesieutre B, Bartholomew E (2004) A review of market monitoring activities at US independent system operators. Working paper in Lawrence Berkeley national Laboratory

Gotts NM, Polhill JG, Law ANR (2003) Agent-based simulation in the study of social Dilemmas. Artif Intell Rev 19(1): 3–26. doi:10.1023/A:1022120928602

Grozev G, Batten D (2005) NEMSIM: practical challenges for Agent-based simulation of energy markets. In the CSIRO Complex Systems Science Annual Workshop. CSIRO Manufacturing and Infrastructure Technology

Grozev G, Batten D, Aanderson M, Lewis G, Mo J, Katzfey J (2005) NEMSIM: agent-based simulator for Australia's national electricity market http://www.siaa.asn.au/get/2411853323.pdf. Cited 1 Aug 2007

Harp SA, Brignone S, Wollenberg BF, Samad T (2000) SEPIA: a simulator for electric power industry agents. IEEE Contr Syst Mag 20(4): 53–69. doi:10.1109/37.856179

Haverkamp DS, Gauch S (1998) Intelligent information agents: review and challenges for distributed information sources. J Am Soc Inf Sci 49(4): 304–311. doi:10.1002/(SICI)1097-4571(19980401)49:4<304::AID-ASI2>3.0.CO;2-L

Homepage MASON (2007). http://cs.gmu.edu/~eclab/projects/mason. Cited 1 Aug 2007

HTC (2007) http://nsr.mij.mrs.org/orgs/htc.honeywell.com.html. Cited 1 Aug 2007

ILOG (2003) ILOG CPLEX 9.0 user's manual. Incline Village, Nevada. http://www.ilog.com/products/cplex. Accessed 3 July 2009

Klusch M, Gerber A (2002) Dynamic coalition formation among rational agents. IEEE Intell Syst 17(3): 42–47. doi:10.1109/MIS.2002.1005630

Koritarov V (2004) Real-world market representation with agents. IEEE Power Energy Mag 2(4):38–46

Luke S, Cioffi-Revilla C, Panait L, Sullivan K (2004) MASON: a new multi-agent simulation toolkit. In: Proceedings of the 2004 SwarmFest Workshop

Luke S, Cioffi-Revilla C, Panait L, Sullivan K, Balan G (2005) MASON: a multiagent simulation environment. Simulation 81(7): 517–527. doi:10.1177/0037549705058073

Macal C, North M (2005) Tutorial on agent based modeling and simulation. In: Kuhl ME, Steiger NM, Armstrong FB, Joines JA (eds) Proceedings of the Winter Simulation Conference. IEEE, Piscataway, pp 2–15

Macal C, North M (2006) Tutorial on agent based modeling and simulation part 2: how to model with agents. In: Perrone LF, Wieland FP, Liu J, Lawson BG, Nicol DM, Fujimoto RM (eds) Proceedings of the Winter Simulation Conference. IEEE, Piscataway, pp 73–83

Minar N, Burkhart R, Langton C, Askenazi M (1996) The swarm simulation system: a toolkit for building multi-agent systems, Santa Fe Institute Working Paper 96-06-042, Santa Fe

MIT (2007) http://education.mit.edu/starlogo/. Cited 1 Aug 2007

Murtagh B, Saunders M (1998) MINOS 5.5 user's guide. Standford University Systems Optimization Laboratory Technical Report SOL83-20R

NetLogo Homepage (2007) Center for connected learning and computer-based modeling. http://ccl.northwestern.edu/netlogo. Cited 1 Aug 2007

North MJ, Conzelmann V, Koritarov C, Macal CM, Thimmapuram P, Veselka T (2002) E-Laboratories: agent-based modeling of electricity markets. In: American Power Conference. Chicago

North MJ, Collier NT, Vos JR (2006) Experiences creating three implementations of the repast agent modeling toolkit. ACM Trans Model Comput Simul 16(1): 1–25. doi:10.1145/1122012.1122013

Praça I, Ramos C, Vale Z, Cordeiro M (2003) MASCEM: a multiagent system that simulates competitive electricity markets. Intell Syst 18(6): 54–60. doi:10.1109/MIS.2003.1249170

Praça I, Ramos C, Vale Z, Cordeiro M (2003b) A new agent-based framework for the simulation of electricity markets. In the 2003 IEEE/WIC International Conference on Intelligent Agent Technology, pp 469–473

Railsback SF, Lytinen SL, Jackson SK (2006) Agent-based simulation platforms: review and development recommendations. Simulation 82(9): 609–623. doi:10.1177/0037549706073695

Repast Homepage (2007) http://repast.sourceforge.net. Cited 1 Aug 2007

Repenning A (1993) Agentsheets: a tool for building domain-oriented dynamic, visual environments. Ph.D. Dissertation, Department of Computer Science, University of Colorado at Boulder, Boulder, Colorado

Resnick M (1994) Learning about life. Artif Life 1:229–241

Resnick M (1996) Beyond the centralized mindset. J Learn Sci 5(1): 1–22. doi:10.1207/s15327809jls0501_1

Repenning A, Citrin W (1993) Agentsheets: applying grid-based spatial reasoning to human-computer interaction. In: Proceedings of 1993 IEEE Symposium on Visual Languages, pp 77–82

Roth AE, Erev I (1994) Learning in extensive-form games: experimental data and simple dynamic models in the intermediate term. Games Econ Behav 8: 164–212. doi:10.1016/S0899-8256(05)80020-X

Samuelson D, Macal C (2006) Agent-based simulation comes of age. OR/MS Today 33(4):34–38

Schrage L (1991) LINDO: an optimization modeling system. Scientific Press, San Francisco

Steels L (1998) The origins of ontologies and communication conventions in multi-agent systems. Auton Agent Multi Agent Syst 1: 169–194. doi:10.1023/A:1010002801935

Sun J, Tesfatsion LS (2006) Dynamic testing of wholesale power market designs: an open-source agent-based framework. Technical Report 12649. Iowa State University, Department of Economics

Sun J, Tesfatsion LS (2007) An gent-based computational laboratory for wholesale power market design. Technical Report 12776. Iowa State University, Department of Economics

Tesfatsion L (2006) Agent-based computational economics: a constructive approach to economic theory, Handbook of Computational Economics, vol. 2, Chap. 16, pp 831–880

Veit DJ, Weidlich A, Yao J, Oren S (2006) Simulating the dynamics in two-settlement electricity markets via an agent-based approach. Int J Manag Sci Eng Manag 1(2):83–97

Veselka TD, Boyd G, Conzelmann G, Koritarov V, Macal CM, North MJ, Schoepfle B, Thimmapuram P (2002) Simulating the behavior of electricity markets with an agent-based methodology: the electric market complex adaptive systems (Emcas) model. Presented in the 22nd International Association for Energy Economics International Conference. http://www.dis.anl.gov/publications/articles/ceeesa_EMCAS_USAEE2002Paper%5B43943%5D.pdf. Accessed 3 July 2009

Wang G, Zhang W, Mailler R, Lesser V (2003) Analysis of negotiation protocols by distributed search. Distributed sensor networks: a multiagent perspective . Kluwer, Dordrecht, pp 339–361

Watkins CJCH, Dayan P (1992) Technical note. Q-learning. Mach Learn 8(3–4): 279–292. doi:10.1007/BF00992698

Weidlich A, Sensfuß F, Genoese M, Veit D (2004) Studying the effects of CO_2 emissions trading on the electricity market–a multi-agent-based approach. In: Proceedings of the 2nd Joint Research Workshop "Business and Emissions Trading". Springer Physica

Weidlich A, Veit D (2008) A critical survey of agent-based wholesale electricity market models. Energy Econ 30:1728–1759. doi:10.1016/j.eneco.2008.01.003 (Elsevier)

Wooldridge M, Jennings NR (1995) Intelligent agents: theory and practice. Knowl Eng Rev 10(2):115–152

Wooldridge M (1997) Agent-based software engineering. IEE Proc Softw Eng 144(1):26–37

Zhang X, Lesser V, Wagner T (2003) Integrative negotiation in complex organizational agent systems. In: Proceedings of the 2003 IEEE/WIC International Conference on Intelligent Agent Technology (IAT 2003), pp 140–146

Zhang X, Lesser V, Wagner T (2004) A layered approach to complex negotiations. Web Intell Agent Sys: Int J 2(2):91–104 (IOS Press)