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# An agent-based approach equipped with game theory: Strategic collaboration among learning agents during a dynamic market change in the California electricity crisis

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ABSTRACT

An agent-based approach is a numerical (computer-intensive) method to explore the complex characteristics and dynamics of microeconomics. Using the agent-based approach, this study investigates the learning speed of traders and their strategic collaboration in a dynamic market change of electricity. An example of such a market change can be found in the California electricity crisis (2000–2001). This study incorporates the concept of partial reinforcement learning into trading agents and finds that they have two learning components: learning from a dynamic market change and learning from collaboration with other traders. The learning speed of traders becomes slow when a large fluctuation occurs in the power exchange market. The learning speed depends upon the type of traders, their learning capabilities and the fluctuation of market fundamentals. The degree of collaboration among traders gradually reduces during the electricity crisis. The strategic collaboration among traders is examined by a large simulator equipped with multiple learning capabilities.

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## 1. Introduction

Game theory has been long serving as a basis of applied mathematics that is used in social sciences (in particular, in economics). The important feature of game theory is that it attempts to mathematically describe human's behavior in a competitive situation where the payoff of a player (Player I) in making a choice depends upon the choice of the other player (Player II). Originally, the game theory was developed to analyze different types of competition where a player performs better at the other expense. The theory is further extended to treat a wide range of interactions among players. Recently, the game theory serves as a conceptual and mathematical foundation to explore a rational side of human decision making (Camerer, 1997).

Game theory has performed an important role in computer science, as well. Researchers in computer science have used it to model interactive computations in complex analysis. In particular, the game theory provides a theoretical basis in the field of a multi-agent system where many different types of software agents direct themselves for their own purposes (e.g., a reward).

An agent-based approach, incorporating the conceptual framework of game theory, has been applied to investigate various complex business systems. For example, Samuelson (2005) discussed applications of the agent-based approach to investigate business complex systems. Makowski et al. (2005) assembled seventeen articles, all of which discussed various linkages between the agent-based approach and business complex systems from the perspective of optimization.

An important feature of the agent-based approach in business applications is its role in modeling and simulation. The structure of a complex system is modeled with different types of agents equipped with multiple learning capabilities. Their learning processes are usually characterized by adaptive behaviors through which agents determine their decisions by interacting with an environment. The proposed model is numerically expressed and examined by a large simulation study. The incorporation of a problem structure into a modeling process, along with a simulation study, provides us with a new type of numerical capability to handle a large social complex system where many components have interactions among them. Consequently, the agent-based approach is gradually recognized as a new promising approach among researchers in social sciences.

The agent-based approach has been recently applied to investigate a dynamic change of wholesale power trading. For example, Bagnall (2000), Bunn and Oliveira (2001), Jacobs (1997), Morikiyo and Goto (2004) developed multi-agent adaptive systems that incorporated a dynamic bidding process in power trading[1].

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[1] The conventional approaches to explore a dynamic market change of the energy industry can be found in this journal (e.g., Chevillon and Rifflart, 2009; Ghaffari and Zare, 2009; Mohammadi, 2009 and Redl et al., 2009). Knittel and Roberts (2005) applied the mean reverting model to predict the price fluctuation of wholesale electricity during the California electricity crisis.

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In addition to such previous studies, Sueyoshi and Tadiparthi (2005, 2007, 2008a,b,c) and Sueyoshi (2010) proposed a use of the agent-based approach that incorporated reinforcement learning and its related learning algorithm into various agents for power trading. These studies applied the agent-based approach to investigate a dynamic change of bidding strategies in US wholesale power exchange markets. The first study (Sueyoshi and Tadiparthi, 2005) discussed how to incorporate self-learning capabilities into the agent-based approach. The second research (Sueyoshi and Tadiparthi, 2007) extended the first study by incorporating two groups of adaptive behaviors into agents. One of the two groups incorporated multiple learning capabilities into agents. The other group incorporated limited learning capability into agents. To extend the applicability of the proposed approach further, the third study (Sueyoshi and Tadiparthi, 2008a) considered various influences of a transmission line limit on the wholesale price of electricity. As a result of incorporating the line limit between power exchange market zones, the third study could enhance the practicality and applicability of the proposed approach. The fourth study (Sueyoshi and Tadiparthi, 2008b) also developed an agent-based simulator, referred to "Multi-Agent Intelligent Simulator (MAIS)," based upon the adaptive behaviors and algorithms explored in the previous studies. As an important application of MAIS, the fifth research (Sueyoshi and Tadiparthi, 2008c) applied the MAIS to investigate reasons regarding why the California electricity crisis occurred in wholesale power trading. Finally, Sueyoshi (2010) compared the computational results of MAIS with those of well-known economic studies on the California electricity crisis (i.e., Borenstein et al., 2002 and Joskow and Kahn, 2002).

*Differences between this study and the previous studies:* All the previous studies opened up a new numerical method to investigate the dynamic change of various business complex systems such as bidding strategies in power exchange markets. That was an important contribution, indeed. However, no previous study investigated how trading agents collaborated with each other in a power exchange market and how the cooperation influenced their learning speeds. The previous studies implicitly assumed that each agent did not have any communication capability to interact with other agents. Each agent attempted to maximize only his reward obtained from a power exchange market without any interaction with other agents. However, such an assumption is often unrealistic in investigating the dynamic change of a power exchange market because real traders always communicate each other in their bidding process. Therefore, the purpose of this study is to investigate the strategic collaboration among agents and its influence on their learning speed in the dynamic change of a power exchange market. This type of research was not sufficiently explored in all the previous studies that applied the agent-based approach to examine the dynamic change of power trading.

To attain the research objective, this study restructures the agent-based approach by "partial reinforcement learning" (Bereby-Meyer and Roth, 2006: BM&R, hereafter). The reinforcement learning, incorporated in the previous studies, assumed that the learning of an adaptive agent always occurred in all trading experiences. Meanwhile, the partial reinforcement learning extends the concept by incorporating both a learning speed of agents and a limited number of their learning chances to obtain rewards. For example, the learning behavior of a trading agent becomes slow under an occurrence of a market fluctuation. Hence, the learning speed of an agent is important in investigating his adaptive behavior. Furthermore, the sustainability of collaboration among agents becomes important in investigating the bidding strategy of adaptive agents. Moreover, an agent cannot always win in a power exchange market. In some trades, he may win and obtain a reward. But, he often loses in the other trades. That is the reality of power trading. Thus, the adaptive behavior of an agent in power trading is characterized by the partial reinforcement learning, not reinforcement learning used in the previous studies. As a result of such an extension to the partial reinforcement learning, the agent-based approach proposed in this study may express more closely the reality of power trading than the previous studies.

The remaining structure of this article is organized as follows: The next section reviews underlying economic concepts and hypotheses examined in this study. Section 3 describes the California wholesale power exchange market. This study is interested in examining the collaborative behavior of power traders during the California electricity crisis because the market has drastically fluctuated during the crisis period. The electricity crisis is a good example of such a dynamic market change. Section 4 discusses the adaptive behavior of trading agents and their algorithms incorporated in the proposed simulator, or MAIS. Section 5 applies the proposed simulator to a data set related to the California power exchange market before and during the crisis period. This study examines the economic assertions related to the learning speed of agents and cooperation among them. Section 6 summarizes this research along with future extensions.

## 2. Economic assertions

In the field of game theory, Professor Roth and his associates made a contribution by incorporating the cognitive aspect of players (corresponding to software agents in this study) in its experimental framework. Before their efforts, all players did not have any behavioral and cognitive aspects such as a utility function and a speculation capability. Professor Roth and his associates incorporated the behavioral and cognitive aspects of players into the game theory so that they developed a new research field in game theory where the behavior of players was examined by various types of game-based experiments. Thus, they made an experimental linkage between mathematical aspects of traditional game theory and cognitive aspects of behavioral science within the boundary of game theory. That is a contribution in game theory, so being a contribution in economics.

The behavioral and cognitive aspects in game theory can be essentially restated by "reinforcement learning". The concept, originated from animal and human learning psychology, has recently gained attention in economics, computer science and other social sciences. The concept indicates that "choices that have led to good outcomes in the past are more likely to be repeated in the future" (Erev and Roth, 1998, p.859). This observation is widely known as "Law of Effect" and is a basic principle of human's adaptive behavior. Robustness on learning is also found in a learning curve that tends to be steep initially and then be flat. The observation is known as "Power Law of Practice". See Erev and Roth (1998, p.859). Both laws have been long served as a theoretical basis for developing various types of adaptive behaviors.

In addition to the two laws on reinforcement learning, Roth and Erev (1995) have provided an important implication regarding adaptive behaviors: "high rationality does not appear to have an advantage over lower rationality in predicting an equilibrium point from mixed strategies within a framework of game theory" (Erev and Roth, 1998, p.857). The implication is important and is referred to as "Erev–Roth's first assertion" in this study. Moreover, in the conclusion of their study (Erev and Roth (1998, p.875), they have left a research agenda: "whether a theory of very high rationality behavior may provide a basis for a predictive theory of observed behaviors." The issue is also important and is referred to as "Erev–Roth's second assertion".

To computerize the two laws on reinforcement learning and the two assertions on adaptive behaviors, the research of Sueyoshi and Tadiparthi (2007) has developed the following two groups of adaptive software agents in order to investigate the dynamics of wholesale electricity trading.

(a) Type I: The first group consists of agents equipped with multiple learning capabilities. Their learning capabilities include a risk-averse utility function and a speculation capability to predict the

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