Journal of Economic Behavior & Organization 82 (2012) 395–419

Contents lists available at ScienceDirect

Journal of Economic Behavior & Organization

journal homepage: www.elsevier.com/locate/jebo

Co-learning patterns as emergent market phenomena: An electricity market illustration

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ARTICLE INFO

Article history:
Received 31 December 2010
Received in revised form 8 June 2011
Accepted 8 August 2011
Available online 27 August 2011

JEL classification:
C6
D4
L1
L2
L9
Q4

Keywords:
Emergence
Co-learning
Double auction
Wholesale electric power market
Capacity withholding
Market power
AMES wholesale power market testbed
Heat maps

ABSTRACT

The definition of emergence remains problematic, particularly for systems with purposeful human interactions. This study explores the practical import of this concept within a specific market context: namely, a double-auction market for wholesale electric power that operates over a transmission grid with spatially located buyers and sellers. Each profit-seeking seller is a learning agent that attempts to adjust its daily supply offers to its best advantage. The sellers are co-learners in the sense that their supply offer adjustments are in response to past market outcomes that reflect the past supply offer choices of all sellers. Attention is focused on the emergence of co-learning patterns, that is, global market patterns that arise and persist over time as a result of seller co-learning. Examples of co-learning patterns include correlated seller supply offer behaviors and correlated seller net earnings outcomes. Heat maps are used to display and interpret co-learning pattern findings. One key finding is that co-learning strongly matters in this auction market environment. Sellers that behave as Gode-Sunder budget-constrained zero-intelligence agents, randomly selecting their supply offers subject only to a break-even constraint, tend to realize substantially lower net earnings than sellers that tacitly co-learn to correlate their supply offers for market power advantages.

1. Introduction

Emergence is an intriguing multi-faceted concept whose meaning remains controversial, particularly for systems involving purposeful human interactions. Consequently, it is of interest to study the practical import of this concept for economics by examining its role in specific realistically rendered economic contexts.

This study examines emergence in an empirically based model of a double-auction market for wholesale electric power. The market operates over a 5-bus transmission grid with spatially located buyers and sellers. Each profit-seeking seller is a learning agent that attempts to adjust its daily supply offers to its best advantage. The sellers are individual learners in the sense that the learning method of each seller is calibrated (pre-tuned) to the attributes of the seller's specific decision environment to capture learning-to-learn effects. However, the sellers are also *co-learners* in the sense that the adjustments of their daily supply offers are in response to past market outcomes that reflect the past supply offer choices of all sellers.

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doi:10.1016/j.jebo.2011.08.003

Each seller in our model can engage in two forms of strategic capacity withholding in an attempt to influence market prices to its own advantage, i.e., in an attempt to exercise *market power*. The seller can engage in *economic capacity withholding* (reporting supply offers with higher-than-true marginal costs), and/or it can engage in *physical capacity withholding* (reporting supply offers with lower-than-true maximum generation capacities). Economic and physical capacity withholding are the two main ways in which real-world energy sellers can exercise market power. Consequently, it is of interest to energy market operators, for market power mitigation purposes, to understand which form of market power affords greatest advantage to energy sellers. Economic capacity withholding is relatively easy to monitor, to the extent that a seller's fuel type gives a strong indication of its true marginal costs. Strategic physical capacity withholding can be difficult to distinguish from outages and other events that cause unintentional reductions in available generation capacity.

Systematic computational experiments are then conducted to explore the emergence of *co-learning patterns*, that is, global market patterns that arise and persist over time as a result of seller co-learning. The specific co-learning patterns of interest here are correlated seller supply offer behaviors and correlated seller net earnings outcomes.

One key finding is that learning strongly matters in our double-auction environment. Sellers that behave as Gode and Sunder (1993, 1997) budget-constrained zero-intelligence agents, randomly selecting their supply offers subject only to a break-even constraint, tend to realize substantially lower net earnings than sellers that tacitly co-learn to correlate their supply offers for market power advantages. A second key finding is that learning-to-learn strongly matters. The co-learning sellers perform much better when the parameters of their learning methods are calibrated to sweet-spot values reflecting the attributes of their particular decision environment, including both own attributes (e.g., size, cost function, and location) and rival seller attributes. A third key finding is that the pure exercise of economic capacity withholding is typically much more profitable for sellers than any use of physical capacity withholding.

A number of previous electricity researchers have separately explored either economic capacity withholding or physical capacity withholding exercised by learning traders, including the current authors. For example, Li and Tesfatsion (2009a) conduct preliminary learning experiments focusing on seller physical capacity withholding. Li et al. (2008, 2009) explore the emergence of spatially correlated price patterns supported by seller co-learning when sellers can learn to exercise economic capacity withholding. Li and Tesfatsion (2011) explore the effects of seller co-learning on total net surplus (efficiency) and the distribution of surplus among sellers, buyers, and the ISO when sellers can learn to exercise economic capacity withholding.

The only previous work we are aware of that permits learning traders to engage simultaneously in both economic and physical capacity withholding is Tellidou and Bakirtzis (2007). The latter authors analyze an electricity market operating over a 2-bus transmission grid in which seller supply offers take the form of an offered quantity and an offered price. The offered quantity can be less than or equal to the seller's true maximum generation capacity, and the offered price can be greater than or equal to the seller's true reservation price. However, the authors do not undertake any comparative analysis to determine the relative advantages to sellers of the two forms of market power exercise. Moreover, all sellers are assumed to use the same identically parameterized learning method.

With regard to the general economics literature, it is rare to see physical capacity withholding treated at all.[1] This could be due, in part, to the analytical complications that arise when physical capacity withholding leads to binding capacity constraints. It could also be due to the folk belief that, when it comes to the exercise of market power, economic and physical capacity withholding are essentially equivalent means. When physical capacity withholding is considered, it is typically within game contexts in which the focus is on the existence of Nash equilibria without consideration of learning capabilities (e.g., Dechenaux and Kovenock, 2007).

We begin our study in Section 2 with a summary discussion of emergence as it has previously been defined and used for economic systems. A key conclusion from this section is that the concept of weak emergence developed by Bedau (1997) is particularly relevant for the study of real-world economic systems – such as electric power markets – whose complex interweaving of physical constraints, institutional rules, and strategic human behaviors renders them analytically intractable. Roughly, Bedau defines a property P of a system to be *weakly emergent* if P can be systematically generated for the system through a finite simulation, but through no other means.

Section 3 presents our wholesale electric power market model. This model is implemented by means of the AMES Wholesale Power Market Testbed (Li and Tesfatsion, 2009b,c; Tesfatsion, 2010), an agent-based computational laboratory that incorporates institutional and structural features characterizing actual U.S. wholesale electric power markets. In keeping with actual practice, AMES implements a two-settlement system consisting of a forward day-ahead market and a real-time balancing market that operate over a high-voltage alternating current (HVAC) transmission grid. The day-ahead market is organized as a double auction in which wholesale buyers submit daily demand bids to buy energy, wholesale sellers submit daily supply offers to sell energy, and "locational marginal prices" are determined locally (for each hour at each grid bus) to maximize total net surplus subject to transmission and generation constraints. Traders in AMES can be modeled as learning agents who adjust their demand bids and supply offers over time in an attempt to exercise market power.

In Section 4 we explain the experimental design used to test for the (weak) emergence of two types of co-learning patterns in our market model: namely, correlated seller supply offer behaviors, and correlated seller net earnings outcomes. In particular, we develop a series of test cases for a 5-bus wholesale electric power market in which the exercise of seller

[1] For example, firm behavior with potentially binding production capacity constraints is only considered within one relatively small section (pp. 211–234) of the well-known 479-page industrial organization textbook by Tirole (2003) used in graduate and advanced undergraduate economics courses.