Eastern Economic Journal, **2011**, **37**, (28–34)

www.palgrave-journals.com/eej/

Agent-based Modeling and Computational Experiments in Industrial Organization: Growing Firms and Industries *in silico*

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This paper discusses the need for, the mechanics of, and some potential application of agent-based modeling and computational analysis in industrial organization.
Eastern Economic Journal (2011) **37,** 28–34. doi:10.1057/eej.2010.30

Keywords: agent-based modeling; industrial organization; out-of-equilibrium dynamics; computational economics

JEL: L1

> "… So much remained to be done. Everything was still in an imperfect state. It was like fishing in a virgin lake: a whopper at every cast, but so many lovely new specimens that the palate never cloyed." [Paul A. Samuelson in his introduction to the enlarged edition of *Foundations of Economic Analysis* [2003]]

INTRODUCTION

My aim in this paper is not to provide an in-depth survey of computational models in industrial organization. Rather, it is to position the agent-based computational modeling approach within the recent developments in industrial organization and offer my perception on the substantial comparative advantage it has over other existing methodologies. I also offer speculations on what this approach may enable us to achieve within the field of industrial organization.

OUT-OF-EQUILIBRIUM DYNAMICS IN INDUSTRIAL ORGANIZATION

Following the seminal work of Bain [1951, 1956], the traditional empirical studies in industrial organization were dominated by inter-industry, cross-section approach. This approach had its conceptual basis on the structure-conduct-performance paradigm which postulated a unidirectional chain of causation running from structure (industry concentration) to conduct (degree of collusion) and from conduct to performance (price-cost margins or profitability). Implicit behind this approach is a research perspective with an exclusive focus on long-run industry equilibrium and its dependence on structural factors. As Schmalensee [1989] put it, "The usual presumption in cross-section work in all fields of economics is that observed differences across observations reflect differences in long-run equilibrium positions."

While the theoretical perspective supporting these empirical studies typically defined long-run equilibrium either with or without entry barriers, the actual *process* of firm entry and exit through which an industry approaches the stable long-run equilibrium remained outside the purview of standard industrial organization literature. Nevertheless, evidence kept accumulating that these *out-of-equilibrium* processes exhibit certain patterns that are qualitatively common to all industries. A case in point is the *shakeout* phenomenon, in which the number of producers initially rises, then declines sharply, eventually converging to a stable level. While there is much broad qualitative commonality in this pattern, the quantitative details of any industry's approach to long-run equilibrium can differ from other industries. These differences can be related to characteristics of the industry such as fixed cost, market size, or other aspects of the market environment to which the firms must learn to adapt over time. Klepper and Graddy [1990] states: "A last observation concerns the enormous variation across new industries in the pace and severity of the prototypical pattern of industry evolution. This suggests that there are important differences across industries in the factors that condition the evolutionary process." To the extent that all industries go through such a shakeout phase during their life cycle, it is important to understand how various industry-specific factors affect the out-of-equilibrium processes of entry and exit as well as the long-run equilibrium that is eventually attained.

Even when an industry enters the long-run equilibrium phase in its life cycle, the ever-present external shocks to its demand and production environments induce perpetual firm entry and exit. Examples of such external shocks include random shifts in consumer preferences, unexpected changes in the relative input prices, or technological innovations that originate from outside of the given industry. That these ongoing processes also exhibit certain regularities is highlighted in Dunne et al. [1988]. They write: " … we find substantial and persistent differences in entry and exit rates across industries. Entry and exit rates at a point in time are also highly correlated across industries, so that industries with higher than average entry rates tend to also have higher than average exit rates. Together these suggest that industry-specific factors play an important role in determining entry and exit patterns." Unfortunately, the standard analytical techniques (based on static equilibrium models) have been inadequate in explaining these patterns. Caves [1998] gets right to the point as he comments on the high infant mortality rates in many industries: "A consequence of entrants' high rates of early mortality is that, as many cross-section studies have reported, industries with high entry rates will also show high exit rates. That is, the data reject the model that pervades our textbooks: optimal-size firms enter an industry when its equilibrium output expands, exit when it contracts, but never do both at the same time."

The shakeouts, persistent firm turnovers, and mortality rates constitute only a small sample of the empirical regularities which have accumulated over years of research in industrial organization. Given the wealth of observations that are to be explained, the time has come for theorists to step up to the challenge of building appropriate models that are not only capable of generating the typical out-of-equilibrium behavior of firms and industries, but also rich enough to explore and identify the linkages that exist between industry-specific factors and the unfolding *process* of industry development.

WHY AGENT-BASED COMPUTATIONAL MODELS?

The call for fully dynamic models of oligopoly interactions with firm entry and exit has been partially responded to by the recent development of Markov-Perfect

Equilibrium (MPE) models [Pakes and McGuire 1994; Ericson and Pakes 1995].[1] These models represent the natural extension of the game-theoretic equilibrium tradition in industrial organization (IO) models. The basic conceptual framework is directly carried over from the standard game-theoretic models of oligopoly, in that firms are endowed with full rationality (optimizing tendencies) and perfect foresight (rational expectation). They maximize the expected net present value of future cash flows, taking into calculation all likely states of its rivals conditional on all possible realizations of industry-wide shocks. Their decision making process uses recursive methodology that entails Bellman equations: The degree of complexity in the model specification and the solution concept requires extensive use of computational methodologies.[2] While it is clear that this approach has the potential to address the issues of industry dynamics described above, its success thus far has been limited due to the well-known "curse of dimensionality." In the words of the practitioners of this approach:

> "The computational burden of computing equilibria is large enough to often limit the type of applied problems that can be analyzed. There are two aspects of the computation that can limit the complexity of the models we analyze; the computer memory required to store the value and policies, and the CPU time required to compute the equilibrium … . [I]f we compute transition probabilities as we usually do using unordered states then the number of states that we need to sum over to compute continuation values grows exponentially in *both* the number of firms and the number of firm-specific state variables." [Doraszelski and Pakes 2007, pp. 1915–1916]

To the extent that a useful model needs to be able to generate outcomes that can match the real-world data and be rich enough to enable comparative dynamics analysis within reasonable CPU time, the curse of dimensionality significantly undermines the effectiveness of MPE models.[3]

Agent-based computational approach offers a viable alternative to the MPE approach. Tesfatsion and Judd [2006] offer a broad definition of agent-based computational economics (ACE) that is useful for our discussion:

> "ACE is the computational study of economic processes modeled as dynamic systems of interacting agents who do not necessarily possess perfect rationality and information. Whereas standard economic models tend to stress equilibria, ACE models stress economic processes, local interactions among traders and other economic agents, and out-of-equilibrium dynamics that may or may not lead to equilibria in the long run. Whereas standard economic models require a careful consideration of equilibrium properties, ACE models require detailed specifications of structural conditions, institutional arrangements, and behavioral dispositions." [Tesfatsion and Judd 2006, p. xi]

In comparing the ACE approach to the MPE approach, the trade-off that we face as a modeler is clear. The forward-looking behavior of the agents (firms) in the MPE models continues the time-honored tradition of the expectations-based decision making by optimizing agents. The consistency it offers with respect to the standard economic analysis is a significant benefit to modeling industry dynamics this way.

The other side of the equation, however, is the severe restriction that the inherent computational difficulties place on the scale and scope of the feasible research questions. By relaxing the assumptions of perfect rationality and perfect foresight, the ACE approach avoids the computational burden at the level of individual agents and reallocates the computational resources thus released to tracking complex inter-firm interactions that generate the out-of-equilibrium dynamics at the industry level. The approach allows for a realistically large number of firms to be active at any time within the model and enables comparative dynamics exercises with considerable flexibility.

Most importantly, an attractive feature of the agent-based approach is its capability to *grow* firms and industries from their birth and computationally track their growth to maturity. The mechanics are as follows: Imagine an industry which has just come into existence through a serendipitous discovery of the market opportunity by an innovator. The characteristics of the market can be parameterized by specifying a demand function or could be derived from a population of (potential) consumers so that the nature of the market can be defined through the specification of the consumers' utilities. There exists a population of heterogeneous agents (all being potential entrants at time zero) with simple rules that dictate their entry and exit decisions.[4] The final component of the model is a set of rules for market interactions that lead to payoffs for individual agents. These payoffs will enter into the entry/exit decision rules of firms as arguments. With the rules and payoffs in place, we then activate these agents and allow time to progress. As firms enter into this new industry, we can track the process of its development in detail by observing the changes in the values of the relevant endogenous structural variables. The comparative dynamics exercise can be carried out by re-running the computational experiments from the beginning under different parameter values.

CASTING THE NET

Given the general framework of agent-based modeling, there are several sub-areas in industrial organization where this approach can be used effectively. I identify below four potential lines of research. First, the issue of shakeouts in young industries is a natural candidate. As pointed out previously, there exists a substantial body of empirical evidence that the shakeout is a universal phenomenon that is observed across industries and across countries. By starting with an empty industry and evolving it through the repeated process of entry, competition, and exit, one can track the endogenous changes in market structure and investigate how parameter values specific to a given industry affect the evolving paths of the endogenous variables as our computational experiment progresses *in silico*. [See Chang [2009a] for an initial attempt.]

Second, as shown by Dunne et al. [1988], the dynamic processes of entry and exit tend to persist over time and exhibit systematic patterns across time and across industries. Such persistent turbulence in market structure is likely to be a manifestation of the regulating tendencies in the market place as it responds to external shocks. These shocks may have their origins in the demand-side or the supply-side of the market. Inter-temporal fluctuations in consumer preferences will affect the attractiveness of an industry and promote entry of new firms and/or exit of incumbent firms. Unexpected technological changes that affect production efficiencies of firms in a non-uniform way can also promote simultaneous occurrences of firm entry and exit in a given industry: Potential entrants with emerging technologies may find the new environment favorable for entry, while incumbents with suddenly outdated technologies may find the same environment inhospitable and thus be forced to exit.[5] Investigating the frequency and magnitude of such turbulence in market structure along the stationary state can give us insight into the causal mechanisms that lie behind the empirical regularities identified through years of cross-section research on structure–performance relationships — for example, Geroski and Schwalbach [1991] and Davies and Geroski [1997]. We can also dig deeper into the endogenous turbulence by asking what happens to the distribution of market shares over time as the industry reacts to these external shocks. This would allow us to investigate the issue of persistence in market leadership and identify industry-specific parameters that affect the degree of such persistence [Sutton 2007].

A topic that has received renewed attention in recent years is the relation between firm size and growth. Much of this interest has been due to the statistical regularities observed in a number of empirical studies. For instance, the probability of firm survival is found to increase with firm's size, but the proportional rate of a firm's growth conditional on its survival tends to decrease in size. Also, for a given size of firm, the proportional rate of growth is smaller for an older firm, but its survival probability tends to be higher. Relatedly, it has also been shown that the (aggregate) distribution of firm sizes obeys the *power law* such that the frequency of a firm size varies as a power of the size [Axtell 2001].[6] In that the agent-based models have the capacity to evolve an industry from its birth, they offer excellent opportunities for examining the underlying determinants of these regularities.

Finally, entrepreneurship has been a much neglected area of research in industrial organization. Entrepreneurial actions, by definition, are out-of-equilibrium phenomenon. As Kirzner [1973] states: ''In equilibrium there is no room for the entrepreneur. When the decisions of all market participants dovetail completely, so that each plan correctly assumes the corresponding plans of the other participants and no possibility exists for any altered plans that would be simultaneously preferred by the relevant participants, there is nothing left for the entrepreneur to do.'' The area of research in IO that comes closest to addressing entrepreneurship is the Schumpeterian dynamics of ''creative destruction'' which is typically modeled in the standard equilibrium framework of rational innovators making investment decisions over cost-reducing opportunities. An agent-based model of market competition with an embedded population of entrepreneurs who have heterogeneous skills in searching for market opportunities may open up an avenue of research that could not be explored with such equilibrium models.

CONCLUDING REMARKS

Given the empirical regularities accumulated over the years, this is an exciting time to be doing research in ACE in IO. There is a great need for a general unifying model of an industry that is capable of replicating these empirical regularities involving firm entry and exit as well as the long-run industry structure and performance as identified by years of empirical research in our field. By growing firms and industries from their birth, agent-based computational models can explore the out-of-equilibrium behavior of firms and the corresponding industry dynamics over time as they work their way toward the long-run industry equilibrium. As Epstein [2006] states: ''If you didn't grow it, you didn't explain it.''

Acknowledgements

I thank my colleagues, Jon Harford and Matthew Henry, for their insightful comments on an earlier version of this paper.

Notes

1. See Doraszelski and Pakes [2007] for a comprehensive survey of this literature.
2. One may question whether real entrepreneurs in a turbulent market environment would be capable, even intuitively, of solving the type of complex optimization problems involved in this approach.
3. It should be noted that substantial efforts have been made in this literature to alleviate the computational burden while remaining within the MPE framework. See, for instance, Pakes and McGuire [2001], Doraszelski and Judd [2004], and Weintraub et al. [2008].
4. There are many ways to introduce agent heterogeneity, but the most obvious would be to assume heterogeneous levels of production efficiency that can be modified over time as firms engage in search for more efficient production methods for the sake of survival. [This is the approach taken in Chang [2009a, b].]
5. See Chang [2009b] for this line of inquiry using an agent-based computational model.
6. See Axtell [1999] for an agent-based model that endogenously generates this type of distribution for firm sizes.

References

Axtell, R. 1999. The Emergence of Firms in a Population of Agents: Local Increasing Returns, Unstable Nash Equilibria, and Power Law Size Distributions, CSED Working Paper No. 3, Brookings Institution.

———. 2001. Zipf Distribution of U.S. Firm Sizes. *Science*, 293: 1818–1820.

Bain, J.S. 1951. Relation of Profit Rate to Industry Concentration: American Manufacturing, 1936–1940. *Quarterly Journal of Economics*, 65: 293–324.

———. 1956. *Barriers to New Competition*. Cambridge: Harvard University Press.

Caves, R.E. 1998. Industrial Organization and New Findings on the Turnover and Mobility of Firms. *Journal of Economic Literature*, XXXVI: 1947–1982.

Chang, M.-H. 2009a. Industry Dynamics with Knowledge-based Competition: A Computational Study of Entry and Exit Patterns. *Journal of Economic Interaction and Coordination*, 4: 73–114.

———. 2009b. Entry, Exit, and the Endogenous Market Structure in Technologically Turbulent Industries, Economics Department Working Paper #6, Cleveland State University.

Davies, S.W., and P.A. Geroski. 1997. Changes in Concentration, Turbulence, and the Dynamics of Market Shares. *The Review of Economics and Statistics*, 79: 383–391.

Doraszelski, U., and A. Pakes. 2007. A Framework for Applied Dynamic Analysis in IO, in *Handbook of Industrial Organization*, edited by M. Armstrong and R. Porter, Volume 3. Amsterdam, the Netherlands: Elsevier B.V.

Doraszelski, U., and K. Judd. 2004. Avoiding the Curse of Dimensionality in Dynamic Stochastic Games, Technical Working Paper No. 304, Cambridge: NBER.

Dunne, T., M.J. Roberts, and L. Samuelson. 1988. Dynamic Patterns of Firm Entry, Exit, and Growth. *Rand Journal of Economics*, 19: 495–515.

Epstein, J.M. 2006. Agent-based Computational Models and Generative Social Science, in *Generative Social Science: Studies in Agent-based Computational Modeling*, edited by J.M. Epstein. Princeton, NJ: Princeton University Press.

Ericson, R., and A. Pakes. 1995. Markov-Perfect Industry Dynamics: A Framework for Empirical Work. *Review of Economic Studies*, 62: 53–82.

Geroski, P.A., and J. Schwalbach, eds 1991. *Entry and Market Contestability: An International Comparison*. Oxford, UK: Basil Blackwell.

Kirzner, I. 1973. *Competition and Entrepreneurship*. Chicago, IL: University of Chicago Press.

Klepper, S., and E. Graddy. 1990. The Evolution of New Industries and the Determinants of Market Structure. *Rand Journal of Economics*, 21: 27–44.

Pakes, A., and P. McGuire. 1994. Computing Markov-Perfect Nash Equilibria: Numerical Implications of a Dynamic Differentiated Product Model. *Rand Journal of Economics*, 25: 555–589.

———. 2001. Stochastic Algorithms, Symmetric Markov Perfect Equilibrium, and the "Curse" of Dimensionality. *Econometrica*, 69: 1261–1281.

Samuelson, P.A. 2003. *Foundations of Economic Analysis*, Enlarged Edition, Cambridge, MA: Harvard University Press.

Schmalensee, R. 1989. Inter-industry Studies of Structure and Performance, in *Handbook of Industrial Organization*, edited by R. Schmalensee and R.D. Willig, Volume 2. Amsterdam, the Netherlands: Elsevier B.V.

Sutton, J. 2007. Market Share Dynamics and the "Persistence of Leadership" Debate. *American Economic Review*, 97: 222–241.

Tesfatsion, L., and K.L. Judd. 2006. *Handbook of Computational Economics*, Volume 2. Agent-based Computational Economics, Amsterdam, the Netherlands: Elsevier B.V.

Weintraub, G., L. Benkard, and B. Van Roy. 2008. Markov Perfect Industry Dynamics with Many Firms. *Econometrica*, 76: 1375–1411.