Encyclopedia of Complexity and Systems Science
Springer-Verlag 2009
10.1007/978-0-387-30440-3_539
Robert A. Meyers

System Dynamics and Its Contribution to Economics and Economic Modeling

Michael J. Radzicki[1]

(1) Worcester Polytechnic Institute, Worcester, USA

Article Outline

Glossary
Definition of the Subject
Introduction
Types of Dynamic Simulation
Translating Existing Economic Models into a System Dynamics Format
Improving Existing Economic Models with System Dynamics
Creating Economic Dynamics Models from Scratch
Model Validity
Controversies
Future Directions
Bibliography

Glossary Stock Stocks, which are sometimes referred to as “levels” or “states”, accumulate (i. e., sum up) the information or material that flows into and out of them. Stocks are thus responsible for decoupling flows, creating delays, preserving system memory, and altering the time shape of flows. - Flow Flows of information or material enter and exit a system's stocks and, in so doing, create a system's dynamics. Stated differently, the net flow into or out of a stock is the stock's rate of change. When human decision making is represented in a system dynamics model, it appears in the system's flow equations. Mathematically, a system's flow equations are ordinary differential equations and their format determines whether or not a system is linear or nonlinear. - Feedback Feedback is the transmission and return of information about the amount of information or material that has accumulated in a system's stocks. When the return of this information reinforces a system's behavior, the loop is said to be positive. Positive loops are responsible for the exponential growth of a system over time. Negative feedback loops represent goal seeking behavior in complex systems. When a negative loop detects a gap between the amount of information or material in a system's stock and the desired amount of information or material, it initiates corrective action. If this corrective action is not significantly delayed, the system will smoothly adjust to its goal. If the corrective action is delayed, however, the system can overshoot or undershoot its goal and the system can oscillate. - Full information maximum likelihood with opti mal filtering FIMLOF is a sophisticated technique for estimating the parameters of a system dynamics model, while simultaneously fitting its output to numerical data. Its intellectual origins can be traced to control engineering and the work of Fred Schwepe. David Peterson pioneered a method for adapting FIMLOF for use in system dynamics modeling.

Definition of the Subject

System dynamics is a computer modeling method that has its intellectual origins in control engineering, management science, and digital computing. It was originally created as a tool to help managers better understand and control corporate systems. Today it is applied to problems in a wide variety of academic disciplines, including economics. Of note is that system dynamics models often generate behavior that is both counterintuitive and at odds with traditional economic theory. Historically, this has caused many system dynamics models to be evaluated critically, especially by some economists. However, today economists from several schools of economic thought are beginning to use system dynamics, as they have found it useful for incorporating their nontraditional ideas into formal models.

Introduction

System dynamics is a computer simulation modeling methodology that is used to analyze complex nonlinear dynamic feedback systems for the purposes of generating insight and designing policies that will improve system performance. It was originally created in 1957 by Jay W. Forrester of the Massachusetts Institute of Technology as a method for building computer simulation models of problematic behavior within corporations. The models were used to design and test policies aimed at altering a corporation's structure so that its behavior would improve and become more robust. Today, system dynamics is applied to a large variety of problems in a multitude of academic disciplines, including economics.

System dynamics models are created by identifying and linking the relevant pieces of a system's structure and simulating the behavior generated by that structure. Through an iterative process of structure identification, mapping, and simulation a model emerges that can explain (mimic) a system's problematic behavior and serve as a vehicle for policy design and testing.

From a system dynamics perspective a system's structure consists of stocks, flows, feedback loops, and limiting factors. Stocks can be thought of as bathtubs that accumulate/de-cumulate a system's flows over time. Flows can be thought of as pipe and faucet assemblies that fill or drain the stocks. Mathematically, the process of flows accumulating/de-cumulating in stocks is called integration. The integration process creates all dynamic behavior in the world be it in a physical system, a biological system, or a socioeconomic system. Examples of stocks and flows in economic systems include a stock of inventory and its inflow of production and its outflow of sales, a stock of the book value of a firm's capital and its inflow of investment spending and its outflow of depreciation, and a stock of employed labor and its inflow of hiring and its outflow of labor separations.

Feedback is the transmission and return of information about the amount of information or material that has accumulated in a system's stocks. Information travels from a stock back to its flow(s) either directly or indirectly, and this movement of information causes the system's faucets to open more, close a bit, close all the way, or stay in the same place. Every feedback loop has to contain at least one stock so that a simultaneous equation situation can be avoided and a model's behavior can be revealed recursively. Loops with a single stock are termed minor, while loops containing more than one stock are termed major.

Two types of feedback loops exist in system dynamics modeling: positive loops and negative loops. Generally speaking, positive loops generate self-reinforcing behavior and are responsible for the growth or decline of a system. Any relationship that can be termed a virtuous or vicious circle is thus a positive feedback loop. Examples of positive loops in economic systems include path dependent processes, increasing returns, speculative bubbles, learning-by-doing, and many of the relationships found in macroeconomic growth theory. Forrester [12], Radzicki and Sterman [46], Moxnes [32], Sterman (Chap. 10 in [55]), Radzicki [44], Ryzhenkov [49], and Weber [58] describe system dynamics models of economic systems that possess dominant positive feedback processes.

Negative feedback loops generate goal-seeking behavior and are responsible for both stabilizing systems and causing them to oscillate. When a negative loop detects a gap between a stock and its goal it initiates corrective action aimed at closing the gap. When this is accomplished without a significant time delay, a system will adjust smoothly to its goal. On the other hand, if there are significant time lags in the corrective actions of a negative loop, it can overshoot or undershoot its goal and cause the system to oscillate. Examples of negative feedback processes in economic systems include equilibrating mechanisms ("auto-pilots") such as simple supply and demand relationships, stock adjustment models for inventory control, any purposeful behavior, and many of the relationships found in macroeconomic business cycle theory. Meadows [27], Mass [26], Low [23], Forrester [12], and Sterman [54] provide examples of system dynamics models that generate cyclical behavior at the macro-economic and micro-economic levels.

From a system dynamics point of view, positive and negative feedback loops fight for control of a system's behavior. The loops that are dominant at any given time determine a system's time path and, if the system is nonlinear, the dominance of the loops can change over time as the system's stocks fill and drain. From this perspective, the dynamic behavior of any economy – that is, the interactions between the trend and the cycle in an economy over time – can be explained as a fight for dominance between the economy's most significant positive and negative feedback loops.

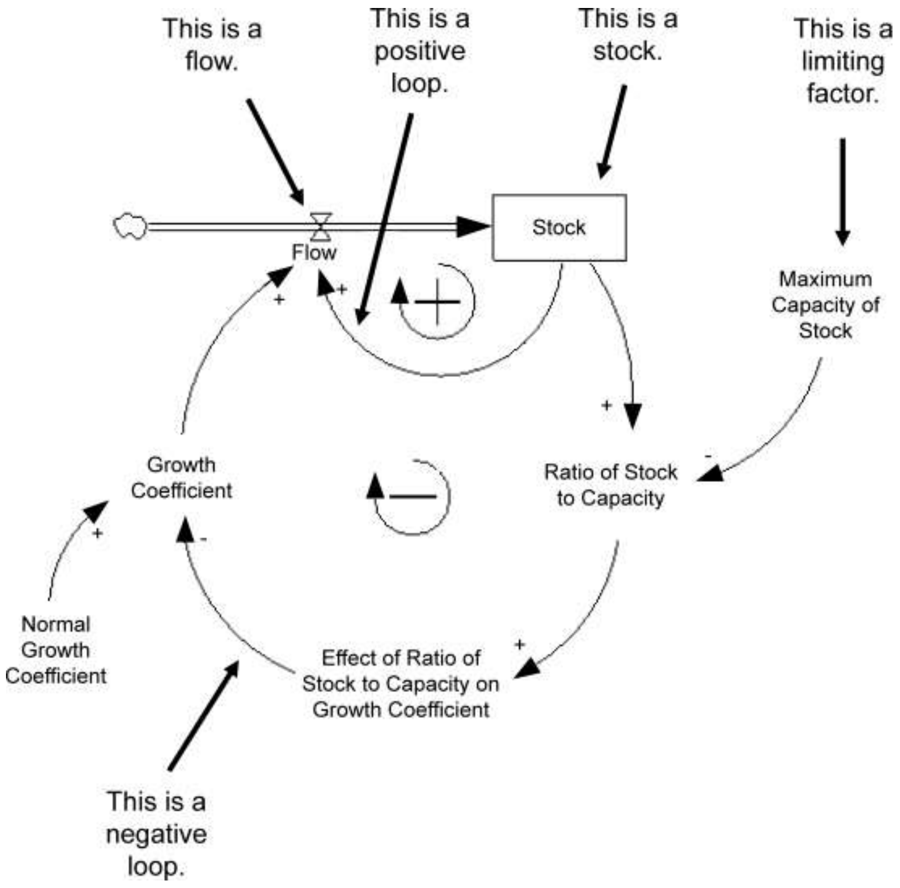

Figure 1 Simple system dynamics model containing examples of all components of system structure

In system dynamics modeling, stocks are usually conceptualized as having limits. That is, stocks are usually seen as being unable to exceed or fall below certain maximum and minimum levels. Indeed, an economic model that can generate, say, either an infinite and/or a negative workforce would be seen as severely flawed by a system dynamicist. As such, when building a model system dynamicists search for factors that may limit the amount of material or information that the model's stocks can accumulate. Actual socioeconomic systems possess many limiting factors including physical limits (e. g., the number of widgets a machine can produce per unit of time), cognitive limits (e. g., the amount of information an economic agent can remember and act upon), and financial limits (e. g., the maximum balance allowed on a credit card). When limiting factors are included in a system dynamics model, the system's approach to these factors must be described. Generally speaking, this is accomplished with nonlinear relationships. Figure 1 presents a simple system dynamics model that contains examples of all of the components of system structure described above.

Types of Dynamic Simulation

From a system dynamics point of view, solving a dynamic model – any dynamic model – means determining how much material or information has accumulated in each of a system's stocks at every point in time. This can be accomplished in one of two ways – analytically or via simulation. Linear dynamic models can be solved either way. Nonlinear models, except for a few special cases, can only be solved via simulation.

Simulated solutions to dynamic systems can be attained from either a continuous (analog) computer or a discrete (digital) computer. Understanding the basic ideas behind the two approaches is necessary for understanding how economic modeling is undertaken with system dynamics.

In the real world, of course, time unfolds continuously. Yet, devising a way to mimic this process on a machine is a bit tricky. On an analog computer, the continuous flow of economic variables in and out of stocks over time is mimicked by the continuous flow of some physical substance such as electricity or water. A wonderful example of the later case is the Phillips Machine, which simulates an orthodox Keynesian economy (essentially the IS-LM model) with flows of colored water moving through pipes and accumulating in tanks. Barr [*2*] provides a vivid description of the history and restoration of the Phillips Machine.

On a digital computer, the continuous flow of economic variables in and out of stocks over time is approximated by specifying the initial amount of material or information in a system's stocks, breaking simulated time into small increments, inching simulated time forward by one of these small increments, calculating the amount of material or information that flowed into and out of the system's stocks during this small interval, and then repeating. The solution to the system will always be approximate because the increment of time cannot be made infinitesimally small and thus simulated time cannot be made perfectly continuous. In fact, on a digital computer a trade-off exists between round-off error and integration error. If the increment of time is made too large, the approximate solution can be poor due to integration error. If the increment of time is made too small, the approximate solution can be ruined due to round-off error.

In system dynamics modeling the “true” behavior of the underlying system is conceptualized to unfold over continuous time. As such, mathematically, a system dynamics model is an ordinary differential equation model. To approximate the solution to a continuous time ordinary differential equation model on a digital (discrete) computer, however, difference equations are used. Unlike traditional difference equation modeling in economics, in which the increment of time is chosen to match economic data (typically a quarter or a year), the increment of time in system dynamics modeling is chosen to yield a solution that is accurate enough for the problem at hand, yet avoids the problems associated with significant round-off and integration error.

The use of difference equations to approximate the underlying differential equations represented by a system dynamics model provides another interesting option when it comes to economic modeling. Since many well known dynamic economic models have been created with difference equations, they can be recast in a system dynamics format by using the difference equations in the system dynamics software literally as difference equations, and not as a tool to approximate the underlying continuous time system. Although doing this deviates from the original ideas embodied in the system dynamics paradigm, it is occasionally done when a modeler feels that analyzing a difference equation model in a system dynamics format will yield some additional insight.

Translating Existing Economic Models into a System Dynamics Format

There are three principle ways that system dynamics is used for economic modeling. The first involves translating an existing economic model into a system dynamics format, while the second involves creating an economic model from scratch by following the rules and guidelines of the system dynamics paradigm. Forrester [*7*], Richardson and Pugh [*47*], Radzicki [*42*], and Sterman [*55*] provide extensive details about these rules and guidelines. The former approach is valuable because it enables well-known economic models to be represented in a common format, which makes comparing and contrasting their assumptions, concepts, structures, behaviors, etc., fairly easy. The latter approach is valuable because it usually yields models that are more realistic and that produce results that are “counterintuitive” [*11*] and thus thought-provoking.

The third way that system dynamics can be used for economic modeling is a “hybrid” approach in which a well known economic model is translated into a system dynamics format, critiqued, and then improved by modifying it so that it more closely adheres to the principles of system dynamics modeling. This approach attempts to blend the advantages of the first two approaches, although it is more closely related to the former.

Generally speaking, existing economic models that can be translated into a system dynamics format can be divided into four categories: written, static (mathematical), difference equation, and ordinary differential equation. Existing economic models that have been created in either a difference equation or an ordinary differential equation format can be translated into system dynamics in a fairly straight-forward manner. For example, Fig. 2 presents Sir John Hicks' [*21*] Multiplier-Accelerator difference equation model in a system dynamics format and Fig. 3 presents the Robert Solow's [52] ordinary differential equation growth model in a system dynamics format.

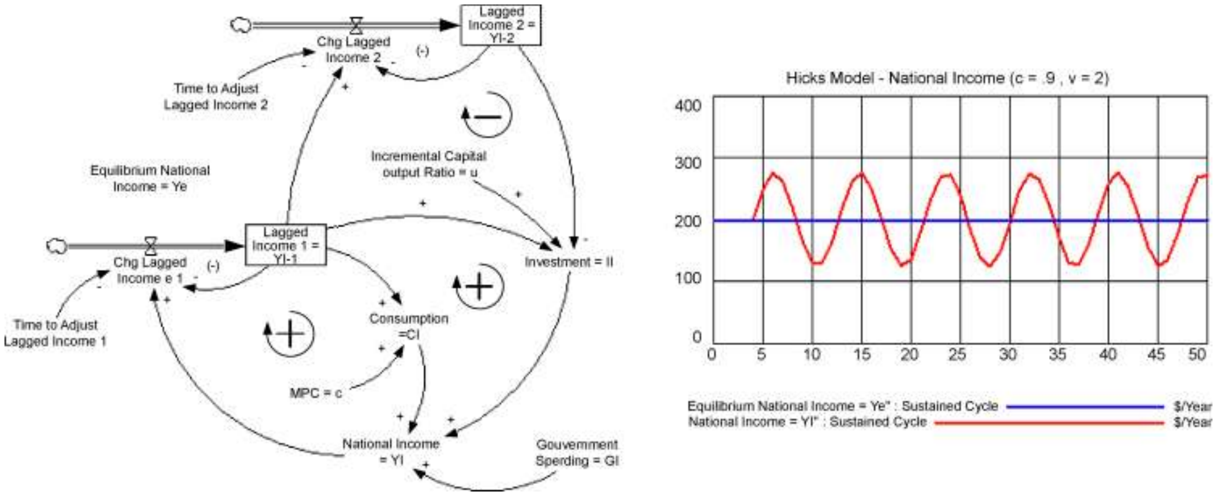

Figure 2 System dynamics representation of John Hicks' multiplier-accelerator difference equation model

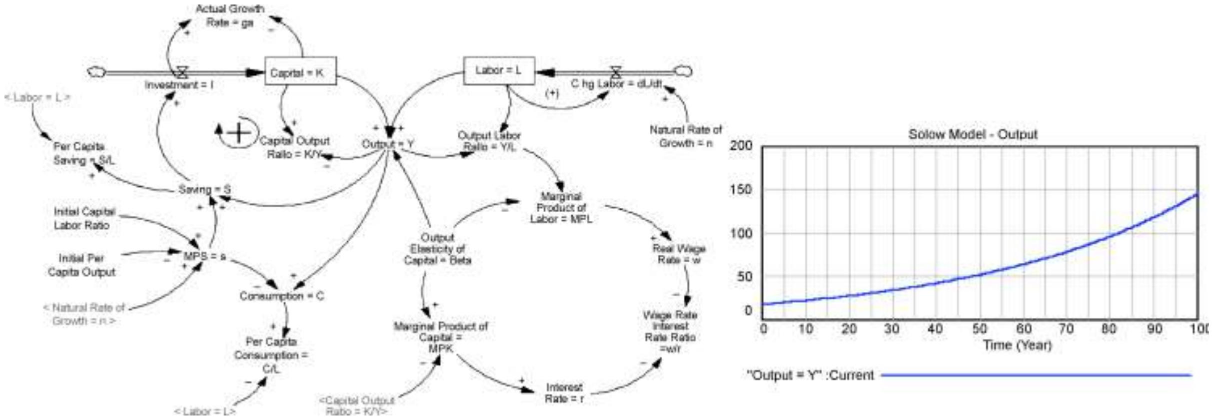

Figure 3 System dynamics representation of Robert Solow's ordinary differential equation growth model

Translating existing static and written economic models and theories into a system dynamics format is a more formidable task. Written models and theories are often dynamic, yet are described without mathematics. Static models and theories are often presented with mathematics, but lack equations that describe the dynamics of any adjustment processes they may undergo. As such, system dynamicists must devise equations that capture the dynamics being described by the written word or that reveal the adjustment processes that take place when a static system moves from one equilibrium point to another.

An interesting example of a system dynamics model that was created from a written economic model is Barry Richmond's [48] model of Adam Smith's *Wealth of Nations*. This model was created principally from Robert Heilbronner's [20] written description of Smith's economic system. A classic example of a static model that has been translated into a system dynamics format is a simple two sector Keynesian cross model, as is shown in Fig. 4.

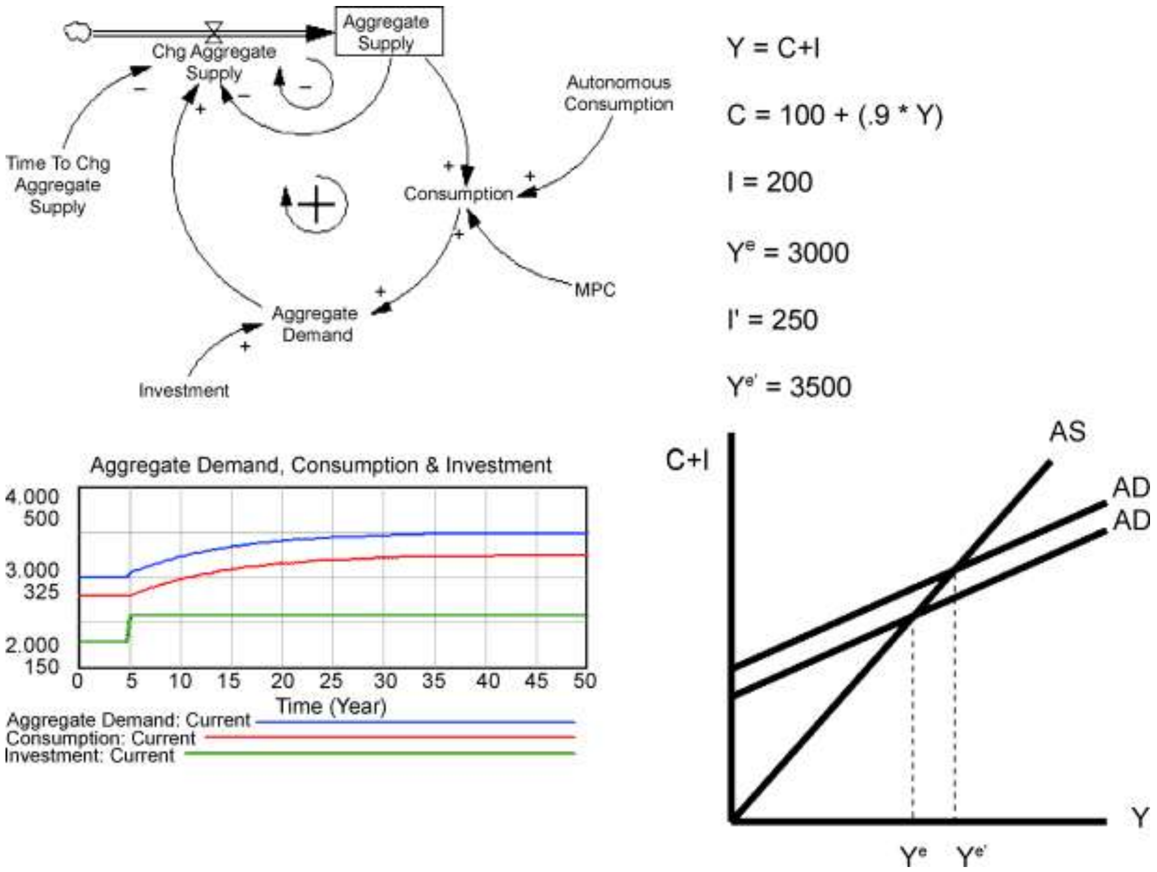

Figure 4 Simple two sector Keynesian cross model in a system dynamics format

Improving Existing Economic Models with System Dynamics

The simple two sector Keynesian cross model presented in Fig. 4 is an example of a well known economic model that can be improved after it has been translated into a system dynamics format. More specifically, in this example the flow of investment spending in the model does not accumulate anywhere. This violates good system dynamics modeling practice and can be fixed. Figure 5 presents the improved version of the Keynesian Cross model, which now more closely adheres to the system dynamics paradigm. Other well known examples of classic economics models that have been improved after they have been translated into a system dynamics format and made to conform more closely with good system dynamics modeling practice include the cobweb model [27], Sir John Hicks' multiplier-accelerator model [23], the IS-LM/AD-AS model [13,59], Dale Jorgenson's investment model [51], William Nordhaus' [34] DICE climate change model [4,5], and basic micro economic supply and demand mechanisms [24]. Low's improvement of Hicks' model is particularly interesting because it results in a model that closely resembles Bill Phillips' [40] multiplier-accelerator model. Senge and Fiddaman's contributions are also very interesting because they demonstrate how the original economic models are special cases of their more general system dynamics formulations.

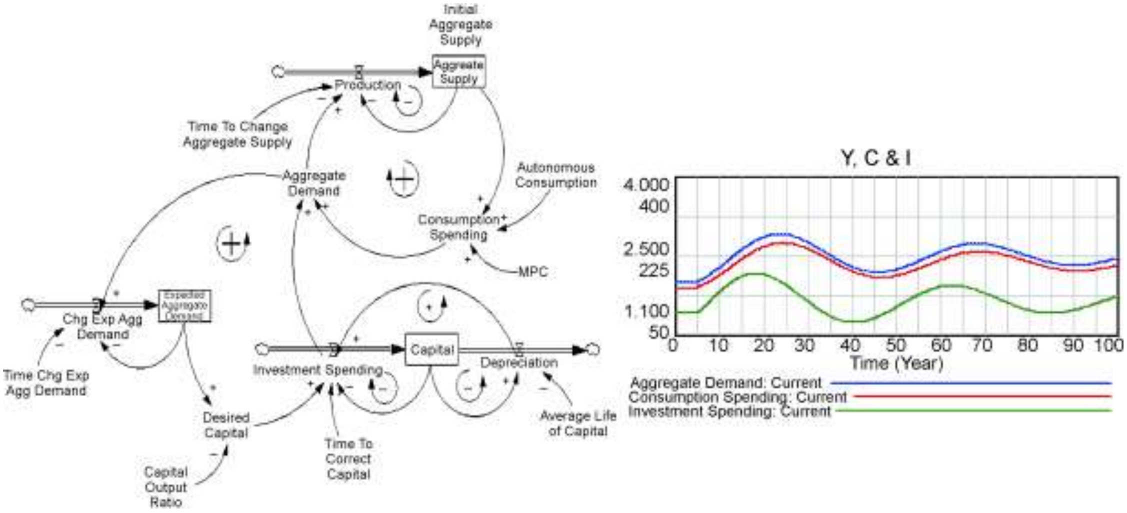

Figure 5 Improved simple two sector Keynesian cross model

Creating Economic Dynamics Models from Scratch

Although translating well known economic models into a system dynamics format can arguably make them easier to understand and use, system dynamicists believe that the "proper" way to model an economic system that is experiencing a problem is to do so from scratch while following good system dynamics modeling practice. Unlike orthodox economists who generally follow a deductive, logical positivist approach to modeling, system dynamicists follow an inductive pattern modeling or case study process. More specifically, a system dynamicist approaches an economic problem like a detective who is iteratively piecing together an explanation at a crime scene. All types of data that are deemed relevant to the problem are considered including numerical, written, and mental information. The system dynamicist is guided in the pattern modeling process by the perceived facts of the case, as well as by real typologies (termed "generic structures" in system dynamics) and principles of systems. Real typologies are commonalities that have been found to exist in different pattern models and principles of systems are commonalities that have been found to exist in different real typologies. Paich [36] discusses generic structures at length and Forrester [8] lays out a set of principles of systems.

Examples of a real typologies in economics include Forrester's [9] *Urban Dynamics* model, which can reproduce the behavior of many different cities when properly parametrized for those cities, and Homer's [22] model of the diffusion of new medical technologies into the market place, which can explain the behavior of a wide variety of medical technologies when properly parametrized for those technologies. Examples of fundamental principles of systems include the principle of accumulation, which states that the dynamic behavior of any system is due to flows accumulating in stocks, and the notion of stocks and flows being components of feedback loops. The parallels for these principles in economics can be found in modern Post Keynesian economics, in which modelers try to build "stock-flow consistent models," and in institutional economics, in which the principle of "circular and cumulative causation" is deemed to be a fundamental cause of economic dynamics. Radzicki [41,43,45] lays out the case for the parallels that exist between methodological concepts in system dynamics and methodological concepts in various schools of economic thought.

The economic models that have been historically created from scratch by following the system dynamics paradigm have tended to be fairly large in scale. Forrester's [12] national economic model is a classic example, as are the macroeconomic models created by Sterman [53], the Millennium Institute [31], Radzicki [45], Wheat [59], and Yamaguchi [60]. Dangerfield [3] has developed a model of Sarawak (E. Malaysia) to analyze and plan for economic transition from a production economy to a knowledge-based one. With the exception of Radzicki [45], whose model is based on ideas from Post Keynesian and institutional economics, these models, by and large, embody orthodox economic relationships.

Model Validity

When a system dynamics model of an economic system that is experiencing a problem is built from scratch, the modeling process is typically quite different from that which is undertaken in traditional economics. As such, the question is raised as to whether or not an original system dynamics model is in any sense "valid".

System dynamicists follow a "pattern modeling" approach [41] and do not believe that models should be judged in a binary fashion as either "valid" or "invalid". Rather, they argue that confidence in models can be generated along multiple dimensions. More specifically, system dynamicists such as Peterson [38], Forrester and Senge [16] and Barlas [1] have developed a comprehensive series of tests that can be applied to a model's structure and behavior and they argue that the more tests a model can pass, the more confidence a model builder or user should place in its results. Even more fundamentally, however, Forrester [13] has argued that the real value generated through the use of system dynamics comes, not from any particular model, but from the modeling *process* itself. In other words, it is through the iterative *process* of model conceptualization, creation, simulation, and revision that true learning and insight are generated, and *not* through interaction with the resulting model.

Another issue that lies under the umbrella of model validity involves fitting models to time series data so that parameters can be estimated and confidence in model results can be raised. In orthodox economics, of course, econometric modeling is almost universally employed when doing empirical research. Orthodox economic theory dictates the structure of the econometric model and powerful statistical techniques are used to tease out parameter values from numerical data.

System dynamicists, on the other hand, have traditionally argued that it is not necessary to tightly fit models to time series data for the purposes of parameter estimation and confidence building. This is because:

1. the battery of tests that are used to build confidence in system dynamics models go well beyond basic econometric analysis;
2. the particular (measured) time path that an actual economic system happened to take is merely one of an infinite number of paths that it could have taken and is a result of the particular stream of random shocks that happened to be historically processed by its structure. As such, it is more important for a model to mimic the basic character of the data, rather than fit it point-by-point [14];
3. utilizing the pattern modeling/case study approach enables the modeler to obtain parameter values via observation below the level of aggregation in the model, rather than

via statistical analysis [18];

4. the result of a system dynamics modeling intervention is typically a set of policies that improve system performance and increase system robustness. Such policies are usually feedback-based rules (i. e., changes to institutional structure) that do not require the accurate point prediction of system variables.

Figure 6 Fit of the Harrod growth model to US macroeconomic data for the years 1929–2002

Although the arguments against the need to fit models to time series data are well known in system dynamics, many system dynamicists feel that it is still a worthwhile activity because it adds credibility to a modeling study. Moreover, in modern times, advances in software technology have made this process relatively easy and inexpensive. Although several techniques for estimating the parameters of a system dynamics model from numerical data have been devised, perhaps the most interesting is David Peterson's [38,39] Full Information Maximum Likelihood with Optimal Filtering (FIMLOF). Figure 5 presents a run from the Harrod growth model, to which an adaptive expectations structure has been added, after it has been fit via FIMLOF to real GDP and labor supply data for the United States economy for the years 1929–2002. The fit is excellent and the estimated parameter values are consistent with those from more traditional econometric studies. See Radzicki [44] for a detailed description of the model and its parameter estimates.

Controversies

Since system dynamics modeling is undertaken in a way that is significantly different from traditional economic modeling, it should come as no surprise that many economists have been extremely critical of some system dynamics models of economic systems. For example, Forrester's [9] *Urban Dynamics* and [10] *World Dynamics* models have come under severe attack by economists, as has (to a lesser degree) his national economic model. On the other hand, the first paper in the field of system dynamics is Forrester [6], which is essentially a critique of traditional economic modeling.

Greenberger et al. [19] present a nice overview of the controversies surrounding the *Urban Dynamics* and *World Dynamics* models. Forrester and his colleagues' replies to criticisms of the *Urban Dynamics* model are contained in Mass [25] and Schroeder et al. [50].

One of the harshest critics of the *World Dynamics* (WORLD2) model has been Nordhaus [33]. Nordhaus [35] has also very critical of the well known follow-up study to *World Dynamics* known as *The Limits to Growth* [28]. Meadows et al. [29,30] contain updates to the original *Limits to Growth* (WORLD3) model, as well as replies to the world modeling critics.

Forrester [12] presents a nice overview of his national economic model, and the critiques by Stolwijk [57] and Zellner [61] are typical of the attitude of the professional economists toward macroeconomic modeling that is undertaken by following the traditional system dynamics paradigm. The criticism of Forrester's national economic model by the economics profession has probably been less severe, relative to the criticisms of the *Urban Dynamics* and world models, because most of its details are still largely unpublished at the time of this writing.

Another interesting and timely example of the sort of controversy surrounding system dynamics modeling in economics is provided by Sterman and Richardson [56]. In this paper they present a technique for testing whether Hubbert's lifecycle method or the geologic analogy method yields superior estimates of the ultimately recoverable amount of petroleum resources. This study was motivated by a disagreement with a traditionally trained economist over the proper way to conceptualize this issue. Sterman and Richardson devised a clever synthetic data experiment in which a system dynamics model serves as the “real world” with a known ultimately recoverable amount of oil. Hubbert's method and the geologic analogy method are then programmed into the model so they can “watch” the data being generated by the “real world” and provide dynamic estimates of the “known” ultimately recoverable stock of oil. The results showed that Hubbert's method was quite accurate, although it had a tendency to somewhat underestimate the ultimately recoverable amount of oil, while the geologic analogy method tended to overshoot the resource base quite substantially.

Future Directions

Historically, system dynamicists who have engaged in economic modeling have almost never been trained as professional economists. As such, they have had the advantage of being able to think about economic problems differently from those who have been trained along traditional lines, but have also suffered the cost of being seen as “amateurs” or “boy economists” [41] by members of the economics profession. The good news is that there are currently several schools of economic thought, populated by professional economists, in which system dynamics fits quite harmoniously. These include Post Keynesian economics, institutional economics, ecological economics, and behavioral economics. Historically, the economists in these schools have rejected many of the tenets of traditional economics, including most of its formal modeling methods, yet have failed to embrace alternative modeling techniques because they were all seen as inadequate for representing the concepts they felt were important. However in the modern era, with computers having become ubiquitous and simulation having become in some sense routine, system dynamics is increasingly being accepted as an appropriate tool for use in these schools of economic thought. The future of economics and system dynamics will most probably be defined by the economists who work within these schools of thought, as well as by their students. The diffusion of system dynamics models of economic systems through their translation into user-friendly interactive “learning environments” that are available over the world wide web will most likely also be of great importance (see [24,59]).

Bibliography

Primary Literature

1. Barlas Y (1989) Multiple Tests for Validation of System Dynamics Type of Simulation Models. Eur J Operat Res 42(1):59–87

2. Barr N (1988) The Phillips Machine. LSE Q Winter 2(4):305–337

3. Dangerfield BC (2007) System dynamics advances strategic economic transition planning in a developing nation. In: Qudrat-Ullah H, Spector M, Davidsen P (eds) Complex decision-making: Theory & practice. Springer, New York, pp 185–209

4. Fiddaman T (1997) Feedback complexity in integrated climate-economy models. Ph D Dissertation, Sloan School of Management, Massachusetts Institute of Technology. Available from http://www.systemdynamics.org/

5. Fiddaman T (2002) Exploring policy options with a behavioral climate-economy model. Syst Dyn Rev 18(2):243–267

6. Forrester J (1957) Dynamic models of economic systems and industrial organizations. System Dynamics Group Memo D-0. Massachusetts Institute of Technology. Available from http://www.systemdynamics.org/

7. Forrester J (1961) Industrial dynamics. Pegasus Communications, Inc., Waltham

8. Forrester J (1968) Principles of systems. MIT Press, Cambridge

9. Forrester J (1969) Urban dynamics. Pegasus Communications, Inc., Waltham

10. Forrester J (1971) World dynamics. Pegasus Communications, Inc., Waltham

11. Forrester J (1975) Counterintuitive behavior of social systems. In: Forrester J (ed) Collected papers of Jay W Forrester, Pegasus Communications, Inc., Waltham, pp 211–244

12. Forrester J (1980) Information sources for modeling the national economy. J Am Statist Assoc 75(371):555–567

13. Forrester J (1985) ‘The’ model versus a modeling ‘process’. Syst Dyn Rev 1(1 and 2):133–134

14. Forrester J (2003) Economic theory for the new millennium. In: Eberlein R, Diker V, Langer R, Rowe J (eds) Proceedings of the Twenty-First Annual Conference of the System Dynamics Society. Available from http://www.systemdynamics.org/

15. Forrester J, Low G, Mass N (1974) The debate on world dynamics: A response to Nordhaus. Policy Sci 5:169–190

16. Forrester J, Senge P (1980) Tests for building confidence in system dynamics models. In: Legasto Jr AA, Forrester JW, Lyneis JM (eds) TIMS Studies in the Management Sciences: System Dynamics, vol 14. North Holland Publishing Company, Amsterdam, pp 209–228

17. Forrester N (1982) A dynamic synthesis of basic macroeconomic theory: Implications for stabilization policy analysis, Ph D Dissertation, Alfred P Sloan School of Management, Massachusetts Institute of Technology. Available from http://www.systemdynamics.org/

18. Graham A (1980) Parameter estimation in system dynamics modeling. In: Randers J (ed) Elements of the system dynamics method. Pegasus Communications, Inc., Waltham, pp 143–161

19. Greenberger M, Crenson M, Crissey B (1976) Models in the policy process: Public decision making in the computer era, Russell Sage Foundation, New York

20. Heilbroner R (1980) The worldly philosophers, 5th edn. Simon & Schuster, New York

21. Hicks J (1950) A contribution to the theory of the trade cycle. Oxford University Press, London

22. Homer J (1987) A diffusion model with application to evolving medical technologies. Technol Forecast Soc Change 31(3):197–218 MathSciNet

23. Low G (1980) The multiplier-accelerator model of business cycles interpreted from a system dynamics perspective. In: Randers J (ed) Elements of the system dynamics method. Pegasus Communications, Inc., Waltham, pp 76–94

24. Mashayekhi A, Vakili K, Foroughi H, Hadavandi M (2006) Supply demand world: An interactive learning environment for teaching microeconomics. In: Grosler A, Rouwette A, Langer R, Rowe J, Yanni J (eds) Proceedings of the of the Twenty-Fourth International Conference of the System Dynamics Society. Available at http://www.systemdynamics.org/

25. Mass N (1974) Readings in urban dynamics, vol I. Wright-Allen Press, Cambridge

26. Mass N (1975) Economic cycles: An analysis of the underlying causes. MIT Press, Cambridge

27. Meadows D (1970) Dynamics of commodity production cycles. Massachusetts MIT Press, Cambridge

28. Meadows D, Meadows D, Randers J, Behrens III W (1972) The limits to growth: A report for the Club of Rome's project on the predicament of mankind. Universe Books, New York

29. Meadows D, Meadows D, Randers J (1992) Beyond the limits: Confronting global collapse, envisioning a sustainable future. Chelsea Green Publishing, White River Junction

30. Meadows D, Meadows D, Randers J (2002) Limits to growth: The 30-year update. Chelsea Green Publishing, White River Junction

31. Millennium Institute (2007) Introduction and Purpose of Threshold 21, http://www.millennium-institute.org/resources/elibrary/papers/T21Overview.pdf

32. Moxnes E (1992) Positive feedback economics and the competition between ‘hard’ and ‘soft’ energy supplies. J Sci Ind Res 51(March):257–265

33. Nordhaus W (1972) World dynamics: Measurement without data. Econom J 83(332):1156–1183

34. Nordhaus W (1992) The “DICE” model: Background and structure of a dynamic integrated climate-economy model of the economics of global warming. Cowles Foundation for Research in Economics at Yale University, Discussion Paper No. 1009

35. Nordhaus W (1992) Lethal model 2: The limits to growth revisited. Brookings Pap Econo Activity 2:1–59

36. Paich M (1985) Generic structures. Syst Dyn Rev 1(1 and 2):126–132

37. Paich M (1994) Managing the global commons. MIT Press, Cambridge

38. Peterson D (1975) Hypothesis, estimation, and validation of dynamic social models – energy demand modeling. Ph D Dissertation, Department of Electrical Engineering, Massachusetts Institute of Technology. Available from http://www.systemdynamics.org/

39. Peterson D (1980) Statistical tools for system dynamics. In: Randers J (ed) Elements of the system dynamics method. Pegasus Communications, Inc., Waltham, pp 226–245

40. Phillips W (1954) Stabilization policy in a closed economy. Econom J 64(254):290–323

41. Radzicki M (1990) Methodologia oeconomiae et systematis dynamis. Syst Dyn Rev 6(2):123–147

42. Radzicki M (1997) Introduction to system dynamics. Free web-based system dynamics tutorial. Available at http://www.systemdynamics.org/DL-IntroSysDyn/index.html

43. Radzicki M (2003) Mr. Hamilton, Mr. Forrester and a foundation for evolutionary economics. J Econom Issues 37(1):133–173

44. Radzicki M (2004) Expectation formation and parameter estimation in nonergodic systems: the system dynamics approach to post Keynesian-institutional economics. In: Kennedy M, Winch G, Langer R, Rowe J, Yanni J (eds) Proceedings of the Twenty-Second International Conference of the System Dynamics Society. Available at http://www.systemdynamics.org/

45. Radzicki M (2007) Institutional economics, post keynesian economics, and system dynamics: Three strands of a heterodox economics braid. In: Harvey JT, Garnett Jr. RF (eds) The future of heterodox economics. University of Michigan Press, Ann Arbor

46. Radzicki M, Sterman J (1994) Evolutionary economics and system dynamics. In: Englund R (ed) Evolutionary concepts in contemporary economics. University of Michigan Press, Ann Arbor, pp 61–89

47. Richardson G, Pugh A (1981) Introduction to system dynamics modeling with DYNAMO. Pegasus Communications, Inc., Waltham

48. Richmond B (1985) Conversing with a classic thinker: An illustration from economics. Users Guide to STELLA, Chapt 7. High Performance Systems, Inc., Lyme, New Hampshire, pp 75–94

49. Ryzhenkov A (2007) Controlling employment, profitability and proved non-renewable reserves in a theoretical model of the US economy. In: Sterman J, Oliva R, Langer R, Rowe J, Yanni J (eds) Proceedings of the of the Twenty-Fifth International Conference of the System Dynamics Society. Available at http://www.systemdynamics.org/

50. Schroeder W, Sweeney R, Alfeld L (1975) Readings in Urban Dynamics, vol II. Wright-Allen Press, Cambridge

51. Senge P (1980) A system dynamics approach to investment function formulation and testing. Soc-Econ Plan Sci 14:269–280

52. Solow R (1956) A contribution to the theory of economic growth. Q J Econom 70:65–94

53. Sterman J (1981) The energy transition and the economy: A system dynamics approach. Ph D Dissertation, Alfred P Sloan School of Management, Massachusetts Institute of Technology. Available at http://www.systemdynamics.org/

54. Sterman J (1985) A behavioral model of the economic long wave. J Econom Behav

Organ 6:17–53

55. Sterman J (2000) Business dynamics: Systems thinking and modeling for a complex world. Irwin-McGraw-Hill, New York

56. Sterman J, Richardson G (1985) An experiment to evaluate methods for estimating fossil fuel resources. J Forecast 4(2):197–226

57. Stolwijk J (1980) Comment on 'information sources for modeling the national economy' by Jay W Forrester. J Am Stat Assoc 75(371):569–572

58. Weber L (2007) Understanding recent developments in growth theory. In: Sterman J, Oliva R, Langer R, Rowe J, Yanni J (eds) Proceedings of the of the Twenty-Fifth International Conference of the System Dynamics Society. Available at http://www.systemdynamics.org/

59. Wheat D (2007) The feedback method of teaching macroeconomics: Is it effective? Syst Dyn Rev 23(4):391–413

60. Yamaguchi K (2007) Balance of payments and foreign exchange dynamics – S D Macroeconomic Modeling (4). In: Sterman J, Oliva R, Langer R, Rowe J, Yanni J (eds) Proceedings of the of the Twenty-Fifth International Conference of the System Dynamics Society. Available at http://www.systemdynamics.org/

61. Zellner A(1980) Comment on 'information sources for modeling the national economy' by Jay W Forrester. J Am Stat Assoc 75(371):567–569

Books and Reviews

62. Alfeld L, Graham A (1976) Introduction to urban dynamics. Wright-Allen Press, Cambridge

63. Lyneis J (1980) Corporate planning and policy design: A system dynamics approach. PA Consulting, Cambridge

64. Meadows D, Meadows D (1973) Toward global equilibrium: Collected papers. Wright-Allen Press, Cambridge

65. Meadows D, Behrens III W, Meadows D, Naill R, Randers J, Zahn E (1974) Dynamics of growth in a finite world. Wright-Allen Press, Cambridge

66. Meadows D, Robinson J (1985) The electronic oracle: Computer models and social decisions. Wiley, New York

67. Richardson G (1999) Feedback thought in social science and systems theory. Pegasus

Communications, Inc., Waltham

68. Sterman J (1988) A skeptic's guide to computer models. In: Grant L (ed) Foresight and National Decisions. University Press of America, Lanham, pp 133–169, Revised and Reprinted in: Barney G, Kreutzer W, Garrett M (1991) Managing a Nation. Westview Press, Boulder, pp 209–230