SYSTEM DYNAMICS: SYSTEMIC FEEDBACK MODELING FOR POLICY ANALYSIS

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Contents

"Que sais-je?" ("What do I know?") (Montaigne)
To the memory of my father who somehow taught me to be a student for life...

Summary

The world is facing a wide range of increasingly complex, dynamic problems in the public and private arenas alike. System dynamics discipline is an attempt to address such dynamic, long-term policy problems. Applications cover a very wide spectrum, including national economic problems, supply chains, project management, educational problems, energy systems, sustainable development, politics, psychology, medical sciences, health care, and many other areas. This article provides a comprehensive overview of system dynamics methodology, including its conceptual/philosophical framework, as well as the technical aspects of modeling and analysis. The article frequently refers to other articles in the same Theme as appropriate. Today, interest in system dynamics and related systemic disciplines is growing very fast. System dynamics can address the fundamental structural causes of the long-term dynamic contemporary socio-economic problems. Its "systems" perspective challenges the barriers that separate disciplines. The interdisciplinary and systemic approach of system dynamics could be critical in dealing with the increasingly complex problems of our modern world in this new century.

1. Introduction

At the start of the new century, the world is facing a wide range of increasingly complex, dynamic problems in the public and private arenas alike: nations desire economic growth, yet growth also results in environmental and ecological—sometimes irreversible—destruction. Chronic high inflation, budget deficits, and simultaneous high unemployment together constitute a persistent problem for many developing countries. There is a widening gap between the so-called "north" and "south" nations and also a widening gap between the poor and the rich in a given nation. Markets—both commodities and financial—generate all sorts of short, medium, and long-term cycles, the uncertainty of which has been a major problem for private and public decision-makers for decades. Thousands of small companies are initiated each year, many enjoying a fast—yet unbalanced—growth, only to be followed by bankruptcy in a few years. Globalization is posing new challenges in the social, economic, and corporate domains. With the unprecedented speed of international communication, the "new" economy means that companies will soon find themselves in a complex network of relationships and only those that can understand its dynamics will be able to compete. We are already experiencing the first worldwide recession of the "new" economy—of the new millennium. In the socio-economic domain, there is a tension between the interests of the nation-states and those of international conglomerates, between increasing international interaction and increasing micro-nationalism. Many nations worldwide face the dilemma between full democracy/human rights and the special measures often needed against terrorism.

The examples listed above have some common defining characteristics: they are all dynamic, long-term policy problems. "Dynamic" means, "changing over time." Dynamic problems necessitate dynamic, continuous managerial action. Optimum oil well location problem may be a very difficult problem, but it is nevertheless a "static" decision problem. The decision is made once, and it is not periodically monitored and adjusted depending on the results. The dynamic problems mentioned above, however, must be continuously managed and monitored. Thus, in the specific context of management and policy making, dynamic problems are the ones that are of persistent, chronic, and recurring nature. We take managerial actions, observe the results, evaluate them and take new actions, yielding new results, observations, further actions, and so on, which constitutes a "closed loop." In other words, most dynamic management problems are "feedback" problems. Feedback loops exist not only between the control action and the system, but also in between the various components within the system. Therefore, it is also said that such dynamic feedback problems are "systemic" in nature, that is, they originate as a result of the complicated interactions between the system variables. Finally, since dynamic management necessitates a stream of dynamic decisions, the research focus should not be the individual decisions, but the rules by which these decisions are made, that is, the "policies." The individual decisions are the outcomes of the application of the adopted policies.

System dynamics discipline emerged in the late 1950s, as an attempt to address such dynamic, long-term policy issues, both in the public and corporate domain. Under the leadership of Jay W. Forrester, a group of researchers at M.I.T. initiated a new field then named Industrial Dynamics. (see "On the history, the present, and the future of system dynamics," EOLSS on-line, 2002). The first application area of the methodology was the strategic management of industrial problems. The main output of this research was the publication of *Industrial Dynamics*, the seminal book that introduced and illustrated the new methodology in the context of some classical industrial/business problems. The next major project was *Urban Dynamics*, presenting a dynamic theory of how the construction of housing and businesses determine the growth and stagnation in an urban area. With this application, "industrial dynamics" method moved to the larger domain of socio-economic problems and was eventually renamed "system dynamics." The second application in the larger socio-economic domain was *World Dynamics* (and *Limits to Growth*). These models show how population growth and economic development policies can interact to yield overshoot and collapse dynamics, when crowding and overindustrialization exceed the finite capacity of the environment. In a short period of time since the late 1970s, applications have expanded to a very wide spectrum, including national economic modeling, supply chains, project management, educational problems, energy systems, sustainable development, politics, psychology, medical sciences, health care, and many other areas. In 1983, the International System Dynamics Society was formed. The current membership of the Society is over 1,000. The number of worldwide practitioners is probably much higher than this number.

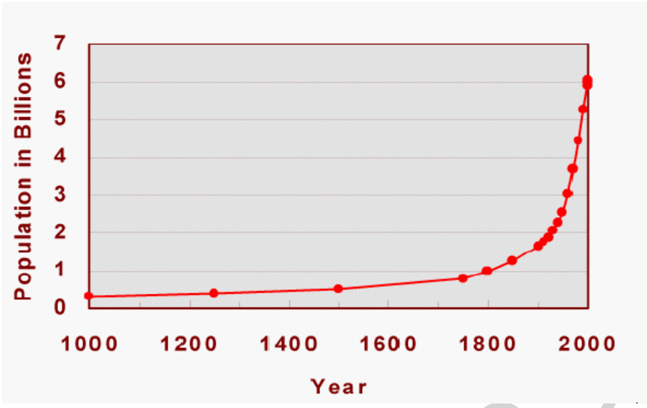
The purpose of the Theme articles (see Knowledge in depth) is to present a thorough exposition of the major aspects of system dynamics method, including its philosophical and historical roots, its technical components, selected exemplary applications, and specific illustrations of its potential in sustainability discourse. The Theme articles, written by experts in respective domains, are grouped under some natural "topics." We start with "System dynamics in action," EOLSS on-line, 2002, a small collection of exemplary applications to give the reader an idea of how the methodology is applied, illustrating the breadth, as well as the depth. The second topic consists of articles discussing the historical, conceptual and philosophical foundations of the field. The third topic of the Theme covers some fundamental concepts and tools of the system dynamics methodology. We next focus on selected technical/mathematical issues in modeling, numerical problems in simulation and other software considerations. The fifth topic is about policy improvement and implementation issues, covering public policy as well as business strategy, plus some general concepts and procedures of implementation. Finally, the last topic consists of six different applications of system dynamics approach and methodology in areas closely related to sustainable development.

The goal of this particular Theme-level article is to provide a comprehensive overview of system dynamics methodology, including its conceptual/philosophical framework, as well as the technical aspects of model construction, analysis and policy design.

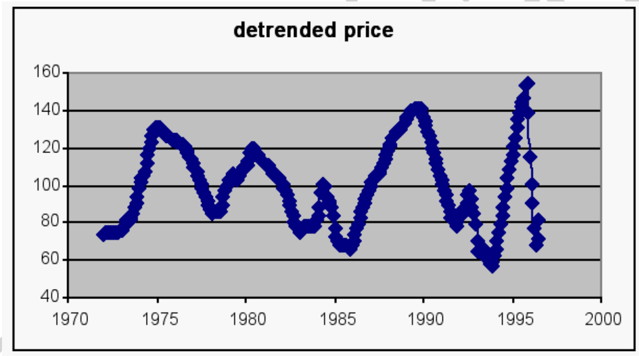
2. Dynamic Problems and Systemic Feedback Perspective

2.1. Dynamic Feedback Problems

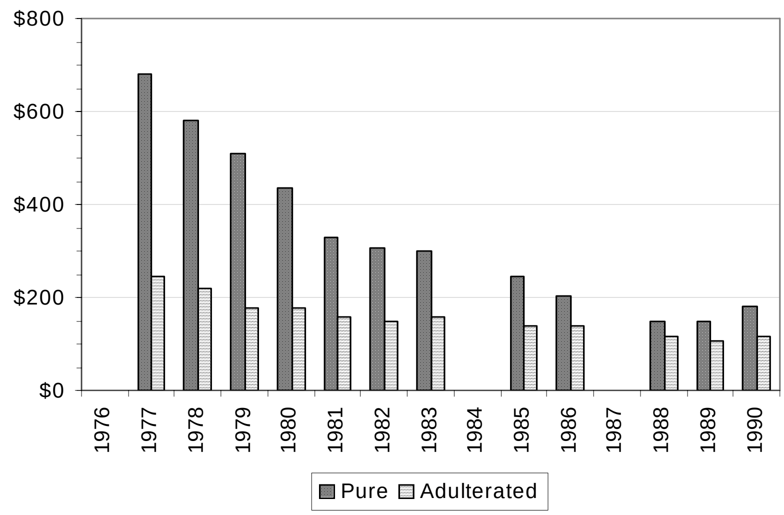
The term “dynamic,” in its general sense, means “in motion” or “changing over time.” Dynamic problems are characterized by variables that undergo significant changes in time. Inventory and production managers must deal with inventories and orders that fluctuate; city administrations face increasing levels of solid waste, air and water pollution; wildlife managers are concerned about declining species diversity worldwide; citizens raise their voices against escalating arms race; at a personal level, we are concerned when our blood pressure or our heartbeat is unstable, or when our temperature goes up; national leaders are worried about increasing unemployment and inflation levels; the small company is in danger when a few years of fast growth is followed by a sharp decline in the market share. In each one of these cases, there are one or more patterns of dynamic behavior that must be managed (controlled, altered or even reversed). Figure 1 illustrates some typical dynamic patterns observed in real life: explosively growing world population, oscillating commodity (pulp) prices, exponentially declining cocaine prices, and growth-then-collapse in revenues (of Atari, Inc). Yet the defining property of a dynamic problem in our sense (in *systemic, feedback* sense) is not merely the variables being dynamic. More critically, in a systemic dynamic problem, the dynamics of the variables must be closely associated with the operation of the *internal structure* of some identifiable system. It is said that the dynamics is essentially caused by the internal feedback structure of the system. (*endogenous* perspective). Thus, oscillating inventories is a systemic, feedback problem because oscillations are typically generated by the interaction of ordering and production policies of managers. It would not be a systemic problem, if the oscillations were determined by an external force like fluctuating weather conditions: although it would still be a dynamic problem in its technical sense. In this latter case, there is not much the inventory managers can do to eliminate or reduce the oscillations. If, as allowed by a new deregulation, a multinational chain colonizes the grocery market, which in turn causes an unavoidable decline in small grocery store sales, this would not be a systemic feedback problem. There is not much “management” the small grocery store owner can do in order to reverse the deregulation or influence the policies of the multinational chain. The importance of the distinction is that if/when the dynamics are dictated by forces external to the system; there is not much space or possibility for managerial control and improvement. Systemic feedback problems on the other hand, necessitate dynamic, continuous managerial action.



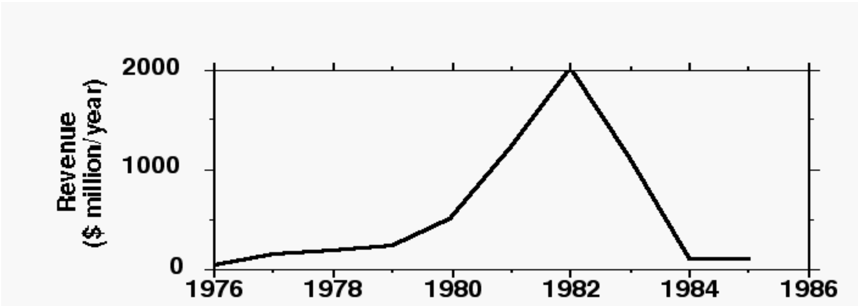
(a) World population growth. (See *The ECOCOSM Paradox*).



(b) U.S.A. pulp prices. (Deflated by CPI and all trends removed).



(c) Retail price per gram of cocaine (in 1990 dollars). (See *A Dynamic Model of Cocaine Prevalence*).



(d) Boom and Bust: Sales and Operating Income of Atari, Inc. (See *Market growth, collapse and faılures to learn from ınteractıve sımulatıon games*).

Figure 1. Illustrations of some typical dynamic patterns observed in real data.

Dynamic management problems in real life are typically feedback problems: we take managerial actions, observe the results, evaluate them and take new actions, yielding new results, observations, further actions, and so on, which constitutes a "feedback loop." Feedback loops exist not only between the managerial action and the system, but also in between the various elements within the system. That is, most dynamic management problems are also "systemic" in nature. The main purpose of system dynamics methodology is to understand the causes of undesirable dynamics and design new policies to ameliorate/eliminate them. Managerial understanding, action and control are at the heart of the method. System dynamics thus focuses on dynamic problems of systemic, feedback nature.

2.2. Systems, Problems, and Models

The term *system* refers to "reality" or some aspects of reality. A system may be defined as a "collection of interrelated elements, forming a meaningful whole." So, it is common to talk about a financial system, a social system, a political system, a production system, a distribution system, an educational system, or a biological system. Each of these systems consists of many elements interacting in a meaningful way, so that the system can presumably serve its "purpose." But it is not trivial for a system to serve its purpose effectively: the global socio-economic system is still facing millions literally starving to death—certainly not an intended result; on the other hand our economic development generates solid waste, air and water pollution levels that threaten the sustainability of life on earth; commodity and financial systems alike generate highly unstable fluctuations worldwide; national economies are often unable to control the simultaneous problems of budget deficit, inflation, and unemployment; small companies typically enjoy a fast growth initially, only to be followed by a sudden collapse—an inevitable result of the unbalanced growth itself; as individuals, we must often deal with health problems such as high blood pressure or cholesterol that our very life style creates, and so on. In short, systems at all levels, scale and scope, while solving one set of problems, simultaneously "produce" other complex challenges.

A common scientific tool used in investigating problems and solutions is *modeling*. A *model* can be defined as “a representation of selected aspects of a real system with respect to some specific problem(s).” Thus, we do not build “models of systems,” but build models of selected aspects of systems to study specific problems. The crucial motivation, purpose that triggers modeling is a problem. The problem can be practical (such as increasing levels of unemployment, declining species population, or collapsing stock prices) or theoretical (such as analyzing a cognitive theory of how knowledge is acquired, or testing the validity of Marx’s theory of class struggle, or whether long-term ecological/environmental sustainability is possible in a capitalist system). In any case, without a problem-purpose, “modeling a system” is meaningless. One does not build a model of a national economy, or a species population, or stock market. One builds a model of some selected elements and relations in a national economy that are likely to have caused a recent upward trend in unemployment; or a model of selected factors believed to play a strong role in an unstoppable decline in the population of a species of concern; or a model that selectively focuses on those factors that are likely to explain a crash in a specific stock market in a specific time period. In the theoretical domain, the principle is the same: one builds a model to study a specific problem/theory so as to contribute to the debate in the relevant community.

Models can be of many types: *Physical* models consist of physical objects (such as scaled models of airplanes, submarines, architectural models, models of molecules). *Symbolic* models consist of abstract symbols (such as verbal descriptions, diagrams, graphs, mathematical equations). System dynamics models are symbolic models consisting of a combination of diagrams, graphs and equations. In another dimension, models can be *static*, representing static balances between variables, assumed to be constant in a time period (such as an architectural model or a mathematical equation representing the relation between price, supply and demand at a point in time). Or they can be *dynamic*, representing how the variables change over time (such as an aircraft simulator to train pilots, Newton’s laws of motion, or a mathematical model of price fluctuations in commodity markets). Another typical classification of models is: *descriptiv*e versus *prescriptive*. Descriptive models describe how variables interact and how the problems are generated “as is,” they do not state how the system “should” function in order to eliminate the problems. Prescriptive (often optimization) models however assume certain “objective functions” and seek to derive the “optimum” decisions that maximize the assumed objective functions. Nonlinear dynamic feedback problems are typically mathematically impossible to be represented and solved by optimization models. System dynamics models are thus descriptive models. The policy recommendations are derived not by the model, but by the modeler, as a result of a series of simulation experiments. Finally, dynamic models can be *continuous* or *discrete* in time. In time-continuous models, change can occur at any instant in time (such as air temperature, humidity, or population of a city), whereas in time-discrete models, change can only occur at pre-defined discrete points in time (such as salaries changing in multiples of months, or student grade point average changing each semester). Real dynamic systems consist of both types of dynamics. So a system dynamics model can be continuous, discrete or even hybrid. In practice, if the discrete time steps associated with the discrete variables is small enough compared to the time horizon of interest (such as a model involving salary dynamics, simulated for decades) one can safely do the time-continuity assumption. The rationale behind this approximation is that continuous-discrete hybrid models can be very cumbersome to build, analyze, and communicate. Continuous system dynamics models are mathematically equivalent to *differential* (or *integral*) equations, whereas discrete models are *difference* equations. In sum, typical system dynamics models are descriptive, continuous or discrete dynamics models, focusing on policy problems involving feedback structures.

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Biographical Sketch

Yaman Barlas received his B.S., M.S. and Ph.D. degrees in Industrial and Systems Engineering, from Middle East Technical University, Ohio University and Georgia Institute of Technology respectively. In 1985, upon receiving his doctoral degree, he joined Miami University of Ohio as an assistant professor of Systems Analysis where he was granted tenure in 1990. He worked as a guest researcher at MIT in the summer of 1990. In 1992, he gave seminars in Istanbul, as a United Nations TOKTEN consultant. He joined Boğaziçi University in 1993, where he is currently working as a professor of Industrial Engineering and directing the SESDYN research laboratory (http://www.ie.boun.edu.tr/labs/sesdyn/). He spent his sabbatical leave at University of Bergen in Norway in 2000.

His interest areas are validation of simulation models, system dynamics methodology, modeling/ analysis of socio-economic problems and simulation as a learning/training platform. He has published numerous articles in journals, proceedings and books, and offered academic and professional seminars nationally and internationally in these areas. He teaches simulation, system dynamics, dynamics of socio-economic systems and advanced dynamic systems modeling. He is a founding member of the System Dynamics Society and member of several other international and national professional organizations. Professor Barlas was the Chair of the 15th International System Dynamics Conference, held in Istanbul in 1997. He is the editor of *System Dynamics Review* for short articles, an invited Honorary Editor of the Encyclopedia of Life Support Systems and a former President of the System Dynamics Society.