System Dynamics, The Basic Elements of

GEORGE P. RICHARDSON
Rockefeller College of Public Affairs and Policy, University at Albany, State University of New York, Albany, USA

Article Outline

Glossary

Endogenous Generated from within. Contrasting with "exogenous," meaning generated by forces external to a system or point of view.

Feedback loop A closed path of causal influences and information, forming a circular-causal loop of information and action.

System dynamics System dynamics is a computer-aided approach to theory-building, policy analysis and strategic decision support emerging from an endogenous point of view.

Definition of the Subject

System dynamics is a computer-aided approach to theory-building, policy analysis, and strategic decision support emerging from an endogenous point of view [18,20]. It applies to dynamic problems arising in complex social, managerial, economic, or ecological systems – literally any dynamic systems characterized by interdependence, mutual interaction, information feedback, and circular causality.

Introduction

The field of system dynamics developed initially from the work of Jay W. Forrester. His seminal book *Industrial Dynamics* [7] is still a significant statement of philosophy and methodology in the field. Within ten years of its publication, the span of applications grew from corporate and industrial problems to include the management of research and development, urban stagnation and decay, commodity cycles, and the dynamics of growth in a finite world. It is now applied in economics, public policy, environmental studies, defense, theory-building in social science, and other areas, as well as its home field, management. The name industrial dynamics no longer does justice to the breadth of the field (for extensive examples, see [20,28], so it has become generalized to system dynamics. The modern name suggests links to other systems methodologies, but the links are weak and misleading. System dynamics emerges out of servomechanisms engineering, not general systems theory or cybernetics [18].

The system dynamics approach involves:

- Defining problems dynamically, in terms of graphs over time.
- Striving for an endogenous, behavioral view of the significant dynamics of a system, a focus inward on the characteristics of a system that themselves generate or exacerbate the perceived problem.
- Thinking of all concepts in the real system as continuous quantities interconnected in loops of information feedback and circular causality.
- Identifying independent stocks or accumulations (levels) in the system and their inflows and outflows (rates).
- Formulating a behavioral model capable of reproducing, by itself, the dynamic problem of concern. The model is usually a computer simulation model expressed in nonlinear equations, but is occasionally left unquantified as a diagram capturing the stock-and-flow/causal feedback structure of the system.
- Deriving understandings and applicable policy insights from the resulting model.
- Implementing changes resulting from model-based understandings and insights.

Mathematically, the basic structure of a formal system dynamics computer simulation model is a system of coupled, nonlinear, first-order differential (or integral) equations,

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{x}(t) = \mathbf{f}(\mathbf{x}, \mathbf{p}) ,$$

where $\mathbf{x}$ is a vector of levels (stocks or state variables), $\mathbf{p}$ is a set of parameters, and $\mathbf{f}$ is a nonlinear vector-valued function. Such a system has been variously called a *state-determined system* in the engineering literature, an *absolute system* [3], an *equifinal system* [32], and a *dynamical system* [16].

Simulation of such systems is easily accomplished by partitioning simulated time into discrete intervals of length $\mathrm{d}t$ and stepping the system through time one $\mathrm{d}t$

at a time. Each state variable is computed from its previous value and its net rate of change $x'(t)$: $x(t) = x(t - \mathrm{d}t) + \mathrm{d}t \cdot x'(t - \mathrm{d}t)$. In the earliest simulation language in the field (DYNAMO) this equation was written with time scripts K (the current moment), J (the previous moment), and JK (the interval between time J and K): $X_{\mathrm{K}} = X_{\mathrm{J}} + \mathrm{DT} \cdot \mathrm{XRATE}_{\mathrm{JK}}$ (see, e. g., [22]). The computation interval dt is selected small enough to have no discernible effect on the patterns of dynamic behavior exhibited by the model. In more recent simulation environments, more sophisticated integration schemes are available (although the equation written by the user may look like this simple Euler integration scheme), and time scripts may not be in evidence. Important current simulation environments include STELLA and iThink (isee Systems, http://www.iseesystems.com/), Vensim (Ventana Systems, http://www.vensim.com/), and Powersim (http://www.powersim.com/).

Forrester's original work stressed a continuous approach, but increasingly modern applications of system dynamics contain a mix of discrete difference equations and continuous differential or integral equations. Some practitioners associated with the field of system dynamics work on the mathematics of such structures, including the theory and mechanics of computer simulation, analysis and simplification of dynamic systems, policy optimization, dynamical systems theory, and complex nonlinear dynamics and deterministic chaos.

The main applied work in the field, however, focuses on understanding the dynamics of complex systems for the purpose of policy analysis and design. The conceptual tools and concepts of the field – including feedback thinking, stocks and flows, the concept of feedback loop dominance, and an endogenous point of view – are as important to the field as its simulation methods.

Feedback Thinking

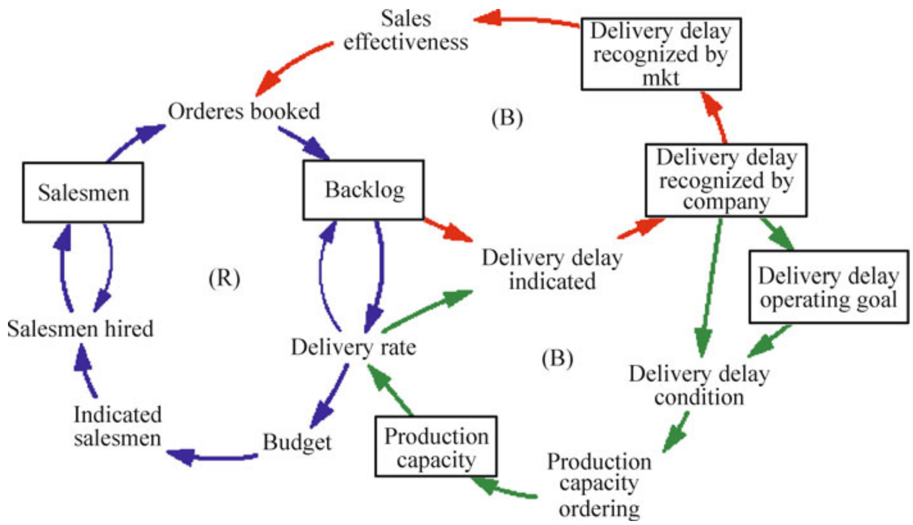
Conceptually, the feedback concept is at the heart of the system dynamics approach. Diagrams of loops of information feedback and circular causality are tools for conceptualizing the structure of a complex system and for communicating model-based insights. Intuitively, a feedback loops exists when information resulting from some action travels through a system and eventually returns in some form to its point of origin, potentially influencing future action. If the tendency in the loop is to reinforce the initial action, the loop is called a *positive* or *reinforcing* feedback loop; if the tendency is to oppose the initial action, the loop is called a *negative, counteracting*, or *balancing* feedback loop. The sign of the loop is called its *polarity*. Balancing loops can be variously characterized as goal-seeking, equilibrating, or stabilizing processes. They can sometimes generate oscillations, as when a pendulum seeking its equilibrium goal gathers momentum and overshoots it. Reinforcing loops are sources of growth or accelerating collapse; they are disequilibrating and destabilizing. Combined, balancing and reinforcing circular causal feedback loops can generate all manner of dynamic patterns.

Feedback loops are ubiquitous in human and natural systems and, under various names and representations, have been widely recognized in popular and scholarly literature. Feedback thought has been present implicitly or explicitly for hundreds of years in the social sciences and literally thousands of years in recorded history [9]. We have the vicious circle originating in classical logic and morphing into common usage, the bandwagon effect, the invisible hand of Adam Smith, Malthus's correct observation of population growth as a self-reinforcing process, Keynes's consumption multiplier, the investment accelerator of Hicks and Samuelson, compound interest or inflation, the biological concepts of proprioception and homeostasis, Festinger's cognitive dissonance, Myrdal's principle of cumulative causation, Venn's idea of a suicidal prophecy, Merton's related notion of a self-fulfilling prophecy, and so on. Each of these ideas can be concisely and insightfully represented as one or more loops of causal influences with positive or negative polarities. Great social scientists and feedback thinkers; great social theories are feedback thoughts. (For a full exposition of the evolution of the feedback concept see [19].)

Loop Dominance and Nonlinearity

The loop concept underlying feedback and circular causality by itself is not enough, however. The explanatory power and insightfulness of feedback understandings also rest on the notions of active structure and loop dominance. Complex systems change over time. A crucial requirement for a powerful view of a dynamic system is the ability of a mental or formal model to change the strengths of influences as conditions change, that is to say, the ability to shift *active* or *dominant structure*.

In a system of equations, this ability to shift loop dominance comes about endogenously from nonlinearities in the system. For example, the S-shaped dynamic behavior of the classic logistic growth model ($\mathrm{d}P/\mathrm{d}t = aP - bP^2$) or similar structures like the Gompertz curve ($\mathrm{d}P/\mathrm{d}t = aP - bP\ln(P)$) can be seen as the consequence of a shift in loop dominance from a positive, self-reinforcing feedback loop (aP) producing exponential-like growth, to a negative



System Dynamics, The Basic Elements of, Figure 1
Core structure of Forrester's market growth model [8], showing a *blue reinforcing loop* underlying the growth (or reinforcing decline) of Salesmen, Orders, and Revenue, a *red balancing loop* containing various delayed recognitions of the company's delivery delay, and a *green balancing loop* responsible for capacity ordering if the delivery delay drops too far below its operating goal

feedback loop ($-bP^2$ or $-bP\ln(P)$) that brings the system to its eventual goal. The shift in loop dominance in these models comes about from the nonlinearity in the second term, which grows faster than the first term and eventually overtakes it. Only nonlinear models can endogenously alter their active or dominant structure and shift loop dominance.

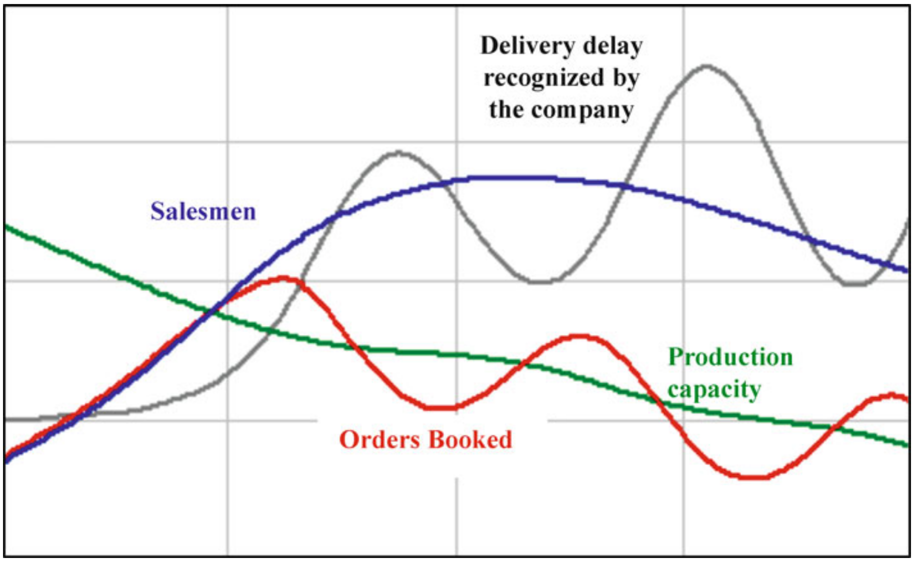
Real systems are perceived to change their active or dominant structure over time, often because of the buildup of internal forces. Thus from a feedback perspective, the ability of nonlinearities to generate shifts in loop dominance is the fundamental reason for advocating nonlinear models of social system behavior.

Figures 1 and 2, abstracted from an early, classic paper [8] illustrate these ideas. In Fig. 1 salesmen (in the blue reinforcing loop) book orders for the company; if enough revenue is generated, there is enough budget to hire more salesmen and corporate growth ensues. Whether salesmen (in this simplified picture) book enough orders depends on the company's delivery delay for the product, as perceived by the market (red balancing loop). The company builds production capacity according to its perceived need, as indicated by its perceived delivery delay and its target for that (green balancing loop).

Figure 2 shows the dynamics this feedback structure endogenously generates. In the early phase, salesmen grow as orders and revenue grow; the system's exponential growth behavior in that phase is generated by the reinforcing salesmen loop. But then the feedback loop dominance soon shifts to the balancing delivery delay loop, which constrains sales effectiveness and brings a halt to growth. The system moves into an oscillatory phase generated by the various monitoring and perception delays around the now dominant red balancing loop. Salesmen eventual peak and decline, as the green production capacity ordering loop fails to keep production capacity sufficient to hold the delivery delays in check.

Thus the dynamic behavior of this system is a consequence of its feedback structure and the nonlinearities that shift loop dominance endogenously over time. The particular decline scenario shown in Fig. 2 illustrates one of the deep insights of the model: the adaptive goal structure, in which the delivery delay operating goal moves slowly to accommodate changes in the company's delivery delay, weakens the green balancing loop trying to bring on capacity. The company never perceives its delivery delay is sufficiently higher than its (sliding) target, so it fails to order sufficient capacity to sustain growth. A fixed goal for the acceptable delivery delay sends a stronger signal, which can turn this corporate decline into oscillating growth [8].

Thus, nonlinearity is crucial to the system dynamics approach. However, it is crucial not merely because of its mathematical properties but because it enables the formalization of a profoundly powerful perspective on theory and policy – the *endogenous point of view*.



System Dynamics, The Basic Elements of, Figure 2
The dynamic behavior of the model shown in Fig. 1, illustrating an early growth phase, which turns into an oscillatory phase as the feedback loop dominance shifts to the *red balancing delivery delay loop*, and results in a long term corporate decline as the *green capacity ordering loop* responds to a sliding operating goal for the acceptable delivery delay

The Endogenous Point of View

The concept of endogenous change is fundamental to the system dynamics approach. It has both philosophical and engineering origins. A deep and lasting insight of the earliest attempts at servomechanisms control is the realization that *the attempt to control a system generates dynamics of its own*, complicating the dynamics trying to be controlled. A governor mechanism imposed to control the speed of a steam engine can generate oscillatory "hunting behavior," as the control system overshoots and undershoots the set point. As it becomes part of the system, the governing mechanism thus generates dynamics of its own.

The insight transfers readily, but with added significance, from engineering systems to people systems: Attempts to control complex human systems – coercing, guiding, managing, governing – generate dynamics of their own. Moreover, some of these endogenously generated dynamics are created by the control mechanisms themselves (like the governor of a steam engine) and some are created by human creative responses to the management efforts (e. g., principal-agent interactions). These natural and human forces, creating counteracting and compensating pressures in response to system control efforts, emerge as complicated circular-causal feedback structures. The often complex, difficult-to-understand dynamics of such management systems are to a great degree a consequence of their internal structures.

To capture and analyze such management complexities, one must look inward to see the ways a complex system naturally responds to system pressures. The endogenous point of view is thus central to the system dynamics approach. It dictates aspects of model formulation: exogenous disturbances are seen at most as *triggers* of system behavior (like displacing a pendulum); the *causes* are contained within the structure of the system itself (like the interaction of a pendulum's position and momentum that produces oscillations). Corrective responses are also not modeled as functions of time, but are dependent on conditions within the system. Time by itself is not seen as a cause in the endogenous point of view.

Theory building and policy analysis are significantly affected by this endogenous perspective. Taking an endogenous view exposes the natural *compensating* tendencies in social systems that conspire to defeat many policy initiatives. Feedback and circular causality are delayed, devious, and deceptive. For understanding, system dynamics practitioners strive for an *endogenous point of view*. The effort is to uncover the sources of system behavior that exist within the structure of the system itself.

System Structure

These ideas are captured almost explicitly in Forrester's [9] organizing framework for system structure:

- Closed boundary
- Feedback loops
- Levels
- Rates
- Goal
- Observed condition
- Discrepancy
- Desired action.

The *closed boundary* signals the endogenous point of view. The word *closed* here does not refer to open and closed systems in the general system sense, but rather refers to the effort to view a system as *causally* closed. The modeler's goal is to assemble a formal structure that can, *by itself*, without exogenous explanations, reproduce the essential characteristics of a dynamic problem.

The causally closed system boundary at the head of this organizing framework identifies the endogenous point of view as the feedback view pressed to an extreme. Feedback thinking can be seen as a *consequence* of the effort to capture dynamics within a closed causal boundary. Without causal loops, all variables must trace the sources of their variation ultimately outside a system. Assuming instead that the causes of all significant behavior in the system are contained within some closed causal boundary forces causal influences to feed back upon themselves, forming causal loops. Feedback loops enable the endogenous point of view and give it structure.

Levels and Rates

Stocks (accumulations, or "levels" in early system dynamics literature) and the flows ("rates") that affect them are essential components of system structure. A map of causal influences and feedback loops is not enough to determine the dynamic behavior of a system. A constant inflow yields a linearly rising stock; a linearly rising inflow yields a stock rising along a parabolic path; a stock with inflow proportional to itself grows exponentially; two stocks in a balancing loop have a tendency to generate oscillations; and so on. For example, the boxes in Fig. 1 represent accumulations in the company and its market; the three stocks in the red balancing loop (the order backlog and the two perceptions of the company's delivery delay) give that loop its tendency to generate oscillations which propagate through out the system. Accumulations are the memory of a dynamic system and contribute to its disequilibrium and dynamic behavior.

Forrester [7] placed the operating policies of a system among its rates, the inflows and outflows governing change in the system. Many of these rates of change assume the classic structure of a negative feedback loop striving to take action to reduce the discrepancy between the observed condition of the system and a goal. The simplest such rate structure results in an equation of the form

$$\text{RATE} = \frac{\text{GOAL} - \text{LEVEL}}{\text{ADJUSTMENT TIME}} ,$$

where ADJUSTMENT TIME is the time over which the level adjusts to reach the goal. This simple formulation reflects Forrester's more general statement about rates in his hierarchy of system structure (above) which can be richly thought of as

$$\text{RATE} = f(\text{DESIRED ACTION})$$

$$\begin{aligned}&\text{DESIRED ACTION}\\ &\quad = g(\text{DESIRED CONDITION},\\ &\qquad\qquad\qquad \text{OBSERVED CONDITION})\end{aligned}$$

$$\text{OBSERVED CONDITION} = h(\text{LEVELS}) ,$$

for some functions f, g, and h representing particular system characteristics.

Operating policies in a management system can influence the *flows* of information, material, and resources, which are the only means of changing the accumulations in the system. While flows can be changed quickly, as a matter of relatively quick decision making, stocks change slowly – they rise when inflows are great than outflows, and decline when inflows are less than outflows.

The simple "tub dynamics" of stocks are clear even to children, yet can be befuddling in complex systems. The accumulation of green house gases in the atmosphere, for example, affects the *flow* of heat energy radiated from the earth. To turn around global warming, the *accumulation* of green house gases must drop far enough to raise radiant energy above the inflow of solar energy, a simple stock-and-flow insight. But to cause the accumulation of green house gases to drop, their generation must fall below their natural absorption rate (another simple stock-and-flow observation). So turning around global warming is a process involving a chain of at least two significant accumulations, and people have trouble thinking it through reliably. The accumulations can only be changed by managing their associated flows. They will change only slowly even if we manage the technical and political pitfalls involved in lowering green house gas production (see [29]).

The significance of stocks in complex systems is vivid in a resource-based view of strategy and policy. Resources that enable a corporation or government to function or flourish are stocks, usually accumulated over long periods of time with significant investment of time, energy, and money. Reputations are also stocks, built over similarly long periods of time. While inadequate by themselves to give a full picture of the dynamics of a complex system, stocks and flows are vital components of system structure, without which fundamental understandings of dynamics are impossible [33].

Behavior is a Consequence of System Structure

The importance of stocks and flows appears most clearly when one takes a *continuous* view of structure and dynamics. Although a discrete view, focusing on separate events and decisions, is entirely compatible with an endogenous feedback perspective, the system dynamics approach emphasizes a continuous view [7]. The continuous view strives to look beyond events to see the dynamic patterns underlying them: model not the appearance of a discrete new housing unit in a city, but focus instead on the rise and fall of aggregate numbers of housing units. Moreover, the continuous view focuses not on discrete decisions but on the *policy structure* underlying decisions: not why this particular apartment building was constructed but what persistent pressures exist in the urban system that produce decisions that change housing availability in the city. Events and decisions are seen as surface phenomena that ride on an underlying tide of system structure and behavior. It is that underlying tide of policy structure and continuous behavior that is the system dynamicist's focus.

There is thus a *distancing* inherent in the system dynamics approach – not so close as to be confused by discrete decisions and myriad operational details, but not so far away as to miss the critical elements of policy structure and behavior. Events are deliberately blurred into dynamic behavior. Decisions are deliberately blurred into perceived policy structures. Insights into the connections between system structure and dynamic behavior, which are the goal of the system dynamics approach, come from this particular distance of perspective.

Suggestions for Further Reading on the Core of System Dynamics

The *System Dynamics Review*, the journal of the System Dynamics Society, published by Wiley, is the best source of current activity in the field, including methodological advances and applications.

The core of a vibrant field is difficult to discern in the flow of current work. However, the works that the field itself singles out as exemplary can give some reliable hints about what is considered vital to the core. In this sense two edited volumes are noteworthy: An early, interesting collection of applications is Roberts [24]; Richardson [21] is a more recent two-volume edited collection in the same spirit, containing prize-winning work in philosophical background, dynamic decision making, applications in the private and public sectors, and techniques for modeling with management.

In addition, the following works, selected from among winners of the System Dynamics Society's *Jay Wright Forrester Award* (see www.systemdynamics.org/Society_Awards.htm), can be considered insightful although implicit exemplars of the core of system dynamics. (Publications are listed beginning with the most recent; see the bibliography for full citations):

- Thomas S. Fiddaman, "Exploring policy options with a behavioral climate-economy model"
- Kim D. Warren, *Competitive Strategy Dynamics*
- Eric F. Wolstenholme, "Towards the Definition and Use of a Core Set of Archetypal Structures in System Dynamics"
- Nelson P. Repenning, "Understanding Fire Fighting in New Product Development"
- John D. Sterman, *Business Dynamics, Systems Thinking and Modeling for a Complex World*
- Peter Milling, "Modeling innovation processes for decision support and management simulation."
- Erling Moxnes, "Not Only the Tragedy of the Commons: Misperceptions of Bioeconomics."
- Jac A. M. Vennix, *Group Model Building: Facilitating Team Learning Using System Dynamics*
- Jack B. Homer, "A System Dynamics Model of National Cocaine Prevalence."
- Andrew Ford, "Estimating the Impact of Efficiency Standards on Uncertainty of the Northwest Electric System."
- Khalid Saeed, *Towards Sustainable Development: Essays on System Analysis of National Policy*
- Tarek Abdul-Hamid and Stuart Madnick, *Software Project Dynamics: An Integrated Approach*
- George P. Richardson, *Feedback Thought in Social Science and Systems Theory*
- Peter M. Senge, *The Fifth Discipline*
- John D. W. Morecroft, "Rationality in the Analysis of Behavioral Simulation Models."
- John D. Sterman, "Modeling Managerial Behavior: Misperceptions of Feedback in a Dynamic Decision Making Experiment."

For texts on the system dynamics approach, see Alfeld and Graham [2], Richardson and Pugh [22], Wolstenholme

[34], Ford [6], Maani and Cavana [11], and the most comprehensive text to date, Sterman [28].

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