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INDUSTRIAL DYNAMICS—AFTER THE FIRST DECADE*

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Industrial dynamics, described as the application of feedback concepts to social systems, is evolving toward a theory of structure in systems as well as being an approach to corporate policy design. In high-order, nonlinear systems, with multiple loops and both positive and negative feedback, are found the modes of behavior which have been so puzzling in management and economics. The time is at hand when more sharply defined concepts and principles can form a core through management education to interrelate the functional areas and to move from static to dynamic understanding of systems. To do so should help close the gap between what the management school can now teach and what the manager must understand if he is to successfully cope with the increasing complexity of our society.

History

A decade has passed since the first work on organizing system concepts into the form which has come to be called "industrial dynamics."[1] Four years before 1956, the Alfred P. Sloan School of Management at MIT had been started with the generous support of Mr. Sloan who believed that a management school in a technical environment would develop in new and important directions that would be different from management schools in other kinds of academic settings. When the author came to the School from his background in feedback control systems, computers, and practicing management, it was for the planned purpose of searching for and developing the linkages which might exist between engineering and management education. It was the expectation that these lay in the areas of operations research and the application of computers to processing management information.

The year 1956–57 was devoted to examining the national activity in operations research which was aimed at bringing mathematics and scientific method to bear on problems in industry. The study indicated that operations research was not dealing effectively with the broader, top-management problems. Most of the work was concentrated on individual decisions structured as open-loop processes, meaning that the inputs to the decision process were considered as unaffected by the decisions themselves. But decisions are made for the purpose of influencing the environment and thereby generating different inputs to succeeding decisions. Although the open-loop assumption simplified analysis, the assumptions underlying the analysis could be invalidated by the closed-loop structure surrounding the actual decision process.

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EDITOR'S NOTE: This article is a companion to the one by H. I. Ansoff and Dennis P. Slevin which appears in this same issue. Because of their relationship, the authors of each have consented to comment on the other article. Their comments are scheduled to appear in the May Issue of *Management Science: Theory*.

[1] This article assumes some familiarity with the basic material in [3].

Furthermore, the mathematical orientation of management science, the concentration on analytical solutions, and the optimization objectives could cope only with rather simple situations. They excluded treatment of the more complex management relationships and also forced neglect of most nonlinear phenomena. It appeared that management science as it then existed did pay its way by working on significant problems. However, there was no substantial body of opinion either inside or outside management science that believed that the problems being attacked were the major ones that made the difference between the companies that succeed and those that stagnate or fail.

The manager's task is to interrelate the separate functions of the company, to create the flows that cause the company and market mutually to support one another, and to interweave the tangible economic variables with the intangible variables of psychology and power structure. None of these was being adequately reached by the management science activities which remained focused on the separate corporate functions and were thus being applied within sharply restricted areas of decision-making. Furthermore, the methods did not seem amenable to much broadening of scope. The manager's principal problems seemed not to lie in decisions taken as isolated events, but rather in policies that deal with streams of decisions and in the structure of the managerial system that interrelates information sources, policy, and action.

The first year of exploration pointed toward the concepts of feedback systems as being much more general, more significant, and more applicable to social systems than had been commonly realized. Feedback system analysis had been extensively applied by engineers in the design of technical devices. Cybernetics as another name for feedback processes was becoming a common word in the biological sciences. The elementary idea of feedback as a circular cause-effect phenomena could be traced back through centuries of economic literature. But even so, the implications, the importance, and the principles of feedback processes were only beginning to be understood. Rather than its having been exhaustively studied, it became increasingly clear that the systems frontier had only begun to open. Feedback processes emerged as universal in social systems and seemed to hold the key to structuring and clarifying relationships that had remained baffling and contradictory.

Aided by a grant from the Ford Foundation, a research program began to relate the elementary concepts of feedback systems, previously developed in the engineering fields, to the processes in social systems. Compatible with the overriding determination to avoid restriction to simple linear systems, analytical treatment was subordinated. One could for the first time turn away from mathematical solutions as the principal means of analysis because computers had reached the point where convenient low-cost system simulation was possible. With simulation available as a procedure for determining the behavior of a model system, it became fruitful to concentrate not on mathematical methods but on the fundamental nature of structure in systems. This work led to a simple and general structure that seemed capable of representing the interactions within any type of system. This generalized structure serves, not only as a framework for organizing observations and experience, but also expedites the simulation stage of system studies. The structure is discussed in a later section.

The past and immediate future of industrial dynamics divides into three periods:

Period One, 1956–1961, Structural Concepts and Steady-State Dynamics. The structure of systems was identified in terms of feedback loops and their component substructures. Examples of system formulation were developed. Applications of the concepts were made to "steady-state" dynamics which concentrate on the fluctuation about equilibrium conditions and which do not involve the processes of growth and decline. This was a period when "enterprise engineering," meaning corporate policy redesign, formed the focus of industrial dynamics. The first period ended with the publication of *Industrial Dynamics* [3].

Phase Two, 1962–1966, Growth Dynamics and General Systems Theory. This has been a period of consolidation and of clarifying the concepts about systems in the social sciences. Experimental educational programs have been tried for the teaching of system principles. It has been a time for reaching a better understanding of the educational materials and methods that will be required to make the concepts of dynamic systems accessible to the average student of management. During this period, examples of industrial dynamics modeling were extended into situations where nonlinearity was of dominant importance. The positive feedback processes of growth in products, companies, and economies have been explored. During this period the view of industrial dynamics was enlarged not only to include the application to enterprise design but also to become a general systems theory to serve as a unifying framework capable of organizing behavior and relationships in areas as diverse as engineering, medicine, management, psychology, and economics. The literature as yet only inadequately conveys the industrial dynamics work of this period in growth and life cycle dynamics [4, 12, 13, 14], education [5, 6, 9], and systems theory [5, 7].

Phase Three, 1967–1975, Foundations and Bridges. The forthcoming period must provide the literature and educational materials necessary to make the theory and the art of dealing with systems more generally accessible. At the present time systems concepts are scattered and incomplete, feedback theory exists in an unnecessarily forbidding mathematical context, and the field lacks interpretation into the specifics of social systems. There needs to be developed a simplified interpretation of the mathematics of feedback processes. The principles of dynamic behavior in systems need to be identified and illustrated with practice exercises for the student. Bridging articles and applications from system theory to a variety of fields need to be presented both to demonstrate generality and to provide guides to the art of system identification and interpretation.

The Present

Industrial dynamics, described as the science of feedback behavior in social systems, is still in a very early stage of development. Many people have been exposed to an introduction to the subject, but, except by serving an apprenticeship in the development of the field, there as yet exists almost no educational opportunity for developing professional competence.

Industrial dynamics is seen very differently by different people. Some observers see it merely as a simulation technique, apparently thinking of industrial dynamics as synonymous with the DYNAMO compiler. The DYNAMO compiler is a computer program for simulating industrial dynamics models but certainly is not the only possible method for such simulation. Simulation, in turn, is not the essence of industrial dynamics; simulation is merely the technique, used because mathematical analytical solutions are impossible, for exposing the nature of system models. To those at the center of industrial dynamics activity, the subject is the interpretation and the extension of feedback system concepts to apply in the multiple-loop, nonlinear systems to which the social processes belong. Although still very incomplete, industrial dynamics is a body of theory dealing with feedback dynamics. It is an identifiable set of principles governing interactions within systems. It is a view of the nature of structure in purposeful systems.

At MIT the first-term subject in industrial dynamics is a popular management elective. Some 120 undergraduate and graduate students take the subject each year. A substantial fraction come from other departments. The subject is also presented to the hundred men in the Sloan Fellow and the Senior Executive Development Programs. But any single-term treatment is incomplete and somewhat superficial. It conveys the importance of structure in determining the behavior of systems. It opens to the student the hope of a better understanding of managerial systems. But it does not prepare the student to proceed by himself. The student exposure in a one-term subject succeeds and fails in much the same way as the book *Industrial Dynamics* [3]. It is probably fair to say that this book seems readable without any specialized training. However, it can be misleading. Many readers can read the book without being aware of the extensive background in feedback systems underlying the presentation. The book does not attempt to convey the principles of feedback systems. The reader without a foundation in feedback dynamics can read the book without realizing that he does not have the conceptual and theoretical background necessary to carry on the work discussed in the book. After reading the book, and apparenly understanding it, such a reader turns to the world around him and finds himself unable, without guidance, to apply successfully the industrial dynamics approach to systems. This difficulty reflects the inadequacy of the present literature and educational materials.

Because the literature is dominated by industrial dynamics applications to production and distribution processes, many people see only a usefulness to such areas and fail to see the generality and the extensions to such areas as marketing, finance, and competition. This deficiency in the literature can now be remedied. Time and effort should yield results.

The very widespread but shallow exposure to industrial dynamics has created acceptance beyond the availability of skilled practitioners to deliver on its hope and promise. Thirty or more universities are teaching industrial dynamics to some extent; in most places this is as part of another course, usually one in production emphasizing simulation methods and the dynamics of production processes. Many industrial organizations have some industrial dynamics activity, but most are in the early phases of self-education. There is widespread international interest in industrial dynamics. The Japanese are active and have translated parts of the American literature and have written a number of original articles. A German translation of *Industrial Dynamics* [3] is in process. Interest in Scandinavia, the United Kingdom, and France seems substantial.

Inquiries in a steady stream come from companies ready to establish industrial dynamics systems groups when competent personnel are available. However, it has become increasingly clear that management schools and social science departments are not training men with adequate depth in system dynamics to fill such openings successfully. The only class of person now having a high probability of success is the one who has studied the dynamics of feedback processes in an engineering curriculum and who then extends and generalizes these ideas in applying them to social systems. The supply of men with such training is much too small to create any significant impression on the demand. The present imbalance between opportunity on the one hand and supply on the other points clearly to the need for much more adequate literature and new and more intensive educational programs.

Status of Feedback System Theory

Because industrial dynamics is a feedback system view of social behavior, it is well to have some perspective on the status of feedback theory. The basic structure of a feedback system is a loop within which the system condition provides the input to a decision process that generates action which modifies the system condition. It is a continuously circulating process. Every decision—personal, corporate, national, international, or in nature—occurs within such a context.

Such an assertion of total generality sometimes generates the response that such a broad concept could have no usefulness because it would not divide the decision-making field into categories—that something which is all-encompassing is empty of meaning. But we do not consider physics meaningless because all its phenomena are based on the atom, nor is biology without interest because of the pervasive presence of the cell. The word "decision" is used here to mean the control of an action stream. Such an action stream may be the time devoted to sleeping in response to one's physical state, the effort to improve products in response to market information about product acceptance, the change in interest rates in response to money supply, the change of prices in response to a worldwide commodity shortage, or the rate of consumption of rabbits as a response to the size of the coyote population. As in these and all other decision streams, the action resulting from the decision stream affects the state of the system to which the decision stream itself is responding.

The feedback concept is found throughout the professional and also the public literature. However, only in the engineering fields is there a well organized body of theory dealing directly with the processes of feedback dynamics. Most of this material is written in the field of electrical engineering. One could probably assemble a forty foot shelf of books devoted to the subject. Consider what such a library would contain. To measure the scope of the existing literature, we might examine four dimensions or characteristics of feedback systems—order, direction of feedback, nonlinearity, and loop multiplicity.

System Order

The order of a system can be expressed in a variety of ways. In physical systems the order is often defined in terms of the number of energy storage elements. In a system expressed as a differential equation the order is equal to the highest derivative. In a system expressed as a series of integrations the order is equal to the number of integrations. In a system expressed in first-order difference equations (which are integrations), the order is equal to the number of difference equations. The number of "levels" (which are first-order difference equations, i.e., integrations) in the industrial dynamics terminology is equal to the system order. In more practical terms, the order of the system is equal to the number of accumulations. In a managerial system one will increase the order of the system for each bank balance, each pool of machine tools, each group of employees, each information variable which measures *average* system activity, and each attitude or psychological state necessary to describe the system.

An examination of the feedback literature will show that most of the material deals with first and second-order systems. A small percent of the literature presses into the region of third and fourth-order systems and beyond. Yet even elementary managerial phenomena usually require a minimum of fifth to twentieth order for adequate representation. Any effort to represent realistically a comprehensive industrial system may carry one well up toward hundredth order. A ratio of ten or more exists between the solidly established literature and the models needed to exhibit the modes of behavior that dominate industrial and economic systems.

Polarity of Feedback

A feedback loop is described as being positive or negative in its action. This refers to the polarity or algebraic sense of influence around the loop.

A positive feedback loop has a polarity around the loop such that action increases a system state to produce still more action. Positive feedback takes place in the build-up phase of an atomic explosion. It occurs in management where salesmen produce revenue to support still more salesmen. Positive feedback is the system description of the process in the multiplication of rabbits. The positive feedback loop produces exponential departure from some reference or neutral condition, often that of zero activity. Positive feedback is an essential process in the growth of products, companies, or countries.

By contrast, the negative feedback loop is goal seeking. A departure from the reference point produces action tending to return the system toward the equilibrium position, that is, the goal. A negative feedback loop may approach its equilibrium position in a smooth, exponential, non-oscillatory manner; or it may approach equilibrium through a decaying series of oscillations; or it can be unstable and produce ever wider swings around the "equilibrium" position which is crossed but to which the system never settles.

Probably 99% of the literature on feedback systems deals with the negative feedback loop. The negative loop is more difficult and subtle than the positive loop. But all processes of growth are manifestations of positive feedback behavior. Positive feedback in the engineering literature is almost entirely omitted because the emphasis has been on steady-state control for maintaining equilibrium conditions. The same is mostly true in the mathematical literature of economics. Positive feedback must usually be omitted from analytical mathematical treatment of linear systems because, in linear systems, a positive feedback loop leads to infinite excursion and destructive consequences. It is in the social and biological systems that so much practical attention is focused on positive feedback behavior. Models of positive feedback processes are feasible when the nonlinearity of natural systems is included to limit the growth phase, or when simulation is used for system study and the time span is short enough that the normal growth phase is not exceeded.

Degree of Nonlinearity

Without attempting a rigorous definition, we can say that a system is nonlinear if it contains a multiplication or division of variables or if it has a coefficient which is a function of a variable. For example, the rate of sale in a market might be expressed as the product of the number of salesmen multiplied by the sales effectiveness, where the sales effectiveness may depend on such things as the price, quality, and delivery delay of the product. But if these latter are variables, the sales rate is a nonlinear function of the variables representing the number of salesmen and the sales effectiveness. Likewise, throughout our social systems, nonlinearity dominates behavior.

In a general sense we can speak of the degree of nonlinearity of a system. The degree of nonlinearity implies the number of policies in the system that are nonlinear and the extent to which the system modes of behavior arise only because of the existence of nonlinearity. The degree of nonlinearity, although not a well-defined concept, might be thought of as a scale extending to the right from an origin, which point of origin represents linear systems. Almost all of mathematical analysis lies within the end point at the beginning of the line. Most of the processes of life and society lie along the scale to the right. Probably not more than two per cent of the literature of feedback systems deals with nonlinear behavior, and that which does is limited to very special cases of nonlinearity.

The importance of nonlinearity is well put by Kovach [10]:

> "We have broken through the sonic barrier, we are well on our way to conquering the thermal barrier and we are now at the threshhold of the nonlinear barrier. Of all three, this last seems the most insurmountable. Strange that these nonlinear phenomena that abound so widely in nature should be so intractable. It is almost as if Man is to be denied a complete knowledge of the universe unless he makes a superhuman effort to solve its nonlinearities. . . . In a way we have been lulled into the belief that everything is ideal, homogeneous, uniform, isotropic, perfect as well as frictionless, weightless, but withal infinitely rigid. . . . We have, so to speak, located a few nonlinear zippers in the blanket of nonlinearity that covers us. Opening these zippers has allowed us to put our hand through and try to fathom the vast unknown in this way. . . . It seems entirely plausible that the qualitative habit of thought will eventually supersede the present quantitative one in mathematics. There are certain indications in science and many in mathematics which point

to the analysis of structure as the mathematics of the future. In simple language, it is not things that matter, but the relations between them."

Multiplicity of Loops

The literature of feedback systems is mostly devoted to the single feedback loop. Only a small fraction of the literature deals with systems of two or more interconnected loops. Yet, to represent adequately managerial systems one must incorporate from two to twenty major loops, each of which may contain many minor loops. For example, a simple structure describing the growth in sales of a new product might contain three nonlinear loops—a positive sales-department loop of salesmen producing orders, leading to revenue to hire more salesmen; a negative market loop in which orders alter backlog to change delivery delay to modify the attractiveness of the product to change order rate; and a negative capital-investment loop where order backlog leads to expanding production to reduce the backlog.

Models of Increased Complexity

As one moves toward systems of greater complexity in any one of the preceding dimensions—order, inclusion of positive feedback, nonlinearity, and multiple loops—he finds that system behavior changes in major qualitative ways. The more complex systems do not merely show extensions of behavior seen in the simpler systems. For example, the way in which system behavior can change as the order of a negative feedback loop is increased is well known. A first-order, negative feedback loop can show only exponential approach to its equilibrium position. A second-order loop introduces the possibility of an entirely new mode of operation—it can show fluctuation either as a damped oscillation or as a growing instability. A third-order system is the simplest one that is capable of showing fluctuations superimposed on exponential growth. More comprehensive models can represent important modes of behavior that are recognized in actual systems but which have previously resisted analysis.

Nonlinearity can introduce unexpected behavior in a system. A nonlinear system can be unstable for small disturbances but stable with sustained oscillation for larger disturbances. Nonlinearity can cause a feedback loop to shift its fundamental character between positive feedback and negative feedback. Nonlinearity can cause dominance to shift from one loop in a system to another. For example, the positive feedback characteristic of growth of a new product can be suppressed and dominance shifted to a negative feedback loop which produces stagnation in product growth.

Multiple feedback loops produce system behavior not seen in the simpler systems. For example, in a multiple loop system containing nonlinearities, the system behavior becomes surprisingly insensitive to change in values of a majority of the system parameters. In some system models, 90% of the parameters can be changed individually by factors of as much as five without substantially affecting the system behavior. Partly this is due to the dilution caused by a single parameter being immersed in a large number of others. But even more importantly, it arises from the intrinsic propensity of a multiple-loop nonlinear system to defeat changes in the system policy statements. A substantial change can be made in a particular policy. However, the system warps in such a way that the incoming information to that decision point shifts to new values which, when processed through the new policy statement, yield approximately the old result. Time after time the manager encounters this in actual practice where a major policy change aimed at correcting a corporate problem seems to produce almost no result. Within a model of a complex system one discovers orderly processes to explain how the system defeats attempts to change its behavior. But there are exceptions, and some of the most useful insights to come from industrial dynamics show which policies in a system have enough leverage so that by changing them one can hope to alter system behavior.

Industrial Dynamics as a Theory of Structure

It may be helpful to distinguish two aspects of a system investigation—that relating to structure, and that relating to dynamic behavior. The two are intimately interwoven because it is the structure which produces the behavior. However, one's interest in the two aspects is sequential. There must be structure before there is a system that can have behavior. It is in the absence of a unifying structure that management education and practice have been particularly weak. Bruner, in his perceptive book on the educational process [1], discusses with great clarity in the first several chapters the importance of structure for expediting learning.

Industrial dynamics is a philosophy of structure in systems. It is also gradually becoming a body of principles that relate structure to behavior. The structure which is codified in industrial dynamics has its counterpart in other fields and other bodies of literature. It is in industrial dynamics, however, that the structure has probably been given its sharpest definition and its most rigorous application.

Structure is seen as having four significant hierarchies:

- The Closed Boundary
  - The Feedback Loop as the Basic System Component
    - Levels (the integrations, or accumulations, or states of a system)
    - Rates (the policy statements, or activity variables, or flows)
      - Goal
      - Observed Conditions
      - Discrepancy between Goal and Observed Conditions
      - Desired Action

At the first hierarchy, industrial dynamics deals with closed systems. This means that the behavior modes of interest are generated within the boundaries of the defined system. It does not mean that one believes that nothing crosses the boundary in the actual system between the part inside the boundary and that outside. Instead, it means that what crosses the boundary is not essential in creating the causes and symptoms of the particular behavior being explored.

Within the boundary, the system is seen as one composed of feedback loops. Every decision exists within one or more such loops. The loops interact to produce the system behavior. A model of a system is formulated by starting with the loop structure, not by starting with components of loops.

At the third hierarchy, loops are themselves composed of two classes of variables, called "levels" and "rates" in the industrial dynamics terminology. Levels are the variables, generated by integration, which at any moment define the state of the system. Rates are the flow variables that depend on the levels and which are integrated to produce the levels. This concept of the level and rate variables appears with different terminology in other fields. The level and rate variables are a necessary and sufficient substructure within the feedback loop.

At the fourth hierarchy, the level variables are generated by the process of integration and have no significant subsubstructure except for the rates flowing into them. The rate variables do have an identifiable subsubstructure. The rate variables are the policy statements of the system and within each there is explicitly or impicitly a statement of the goal of that decision-making point in the system, the observed condition, a discrepancy based on the relationship of goal and observed condition, and the desired action that results from the discrepancy.

The Closed Boundary

The feedback loop is fundamentally a closed process in which a decision, acting through time delay and distortion, influences the state of the system which, after further time delay and distortion, is detected as the observed state of the system. The focus of attention is on how this loop operates. Forces may impinge on the loop from the outside, but our interest is in how the characteristics of the loop itself cause it to amplify or attenuate disturbances or produce growth. The boundary encloses those elements necessary to give the system its intrinsic character. The boundary implies dynamic independence in the sense that any variable crossing the boundary from the outside is not itself a function of the activity within the boundary. Anything on the outside is essentially random or independent of anything on the inside. There are no closed loops of significance to the particular study going from inside the system to outside of the boundary and returning.

Where to draw the boundary depends intimately on the specific system behavior being studied. If one's interest is restricted to a particular mode of behavior, the boundary must necessarily include those elements which generate the mode. Focusing attention on a different behavior mode may well produce substantial changes in the boundary. For an industrial system model, the boundary should include those aspects of the company, the market, the competitors, and the environment which are just sufficient to produce the behavior being investigated. Anything not essential to producing the mode of behavior under study should be left outside the system boundary. Perhaps the point can be illustrated by a recurring example in our Industrial Dynamics Summer Session Programs. The participants go through all of the stages of defining a system, building a model of that system, and examining the dynamic behavior through computer simulation. The price and supply instability in a commodity market is often taken as a vehicle. The problem starts at the simplest level of showing how the supply and consumption responses to price can cause a recurring imbalance between supply and demand. Because government price support programs play a conspicuous part in many commodities, Summer Session participants often feel compelled to incorporate such government activity in the first model. But such a step should be guided by answering this question: "Is the government activity *essential* to *creating* the fluctuation of price and supply, the fundamental cause of which is being explored?" Of course it is not. Commodity prices have been unstable long before there were government price support programs. Price support programs may be helpful or harmful, but they are not necessary in demonstrating the classic and fundamental processes of price and supply instability

The concept of the closed boundary seems elementary yet it is apparently hard to grasp. It asserts that exogenous variables are not the key to the character of the system. Test inputs to a system may be used for study, but they are for the purpose of causing the system to divulge its inherent nature.

The Feedback Loop

The feedback loop is seen as the basic structural element of systems. It is the context within which every decision is made. Every decision is responsive to the existing condition of the system and influences that condition. This is a statement equally true for the forces that control the flow of electricity into a capacitor, for the conscious decisions of the individual or the manager, and for the selective decisions of nature that fit species to the environment by the processes of evolution. The skilled industrial dynamics analyst operates through an iterative process that cycles through the four hierarchies of structure. Yet the focus is always on the higher levels, until these have been satisfactorily established, before devoting much attention to the lower levels. In other words, establishing the system boundary comes first. The second stage is the identification of feedback loops and should come before the detailing of the level and rate substructure. It is here that the man without a solid background in the dynamic nature of feedback systems is at his greatest disadvantage. He is not able to correlate observed symptoms and behavior with probable loop structures. He does not see in the history of a real life situation the evidence that points toward the significance of the different positive and negative feedback loops and their interactions.

Levels and Rates

The industrial dynamics structure recognizes two classes of fundamental system variables as being necessary and sufficient. (The auxiliary equations are algebraically part of the rate equations. The first-order smoothing equations can be decomposed into a simple level equation and two rate equations.) The level equations at any moment in time describe the condition or state of the system. The level variables carry the continuity of the system from the present toward the future and provide the information on which rates of flow are based. The rate variables are the activity or flow variables. The rates change the values of the levels. The level equations are integrations which accumulate the effects of the rates. The rate equations are algebraic expressions without reference to time.

The rate and level concepts are found in the literature of many fields. In economics, the levels are often referred to as stocks and the rates as flows or activity. In engineering feedback systems the "state variable approach" shows increasing prominence. Some quotations from engineering convey the same ideas that are associated with the industrial dynamics level variables. "The state variable approach aids conceptual thinking about these problems, and nonlinear system problems as well. Furthermore, it provides a unifying basis for thinking about linear and nonlinear problems . . . the state of the network is related to the memory of the network . . . heuristically, the state of a system separates the future from the past, so that the state contains all the relevant information concerning the past history of the system required to determine the response for any input . . . the manner in which a system reaches a present state does not affect the future output. The present state of a system and the present and future inputs to a system uniquely determine the present and future outputs . . . the outputs of the integrators in the simulation diagram are used as the components of the state vector . . . although the outputs of the integrators in the simulation diagram form a natural state vector, these variables may not be physically measurable in a system," [2, Chapter 5].

In business, the financial accounting statement implicitly recognizes level and rate variables by separating these onto the balance sheet and the profit and loss statement. The balance sheet gives the present financial condition or state of the system as it has been created by accumulating or integrating the past rates of flow. The profit and loss variables (if one overlooks the fact that they do not represent instantaneous values but are instead averages over some period of time) are the rates of flow which cause the level variables in the balance sheet to change.

The same concept of level and rate variables, cast in a different terminology, can be found in the field of psychology where we might quote from the foreword by Cartwright to a book of papers by Lewin. "The most fundamental construct for Lewin is, of course, that of 'field.' All behavior (including action, thinking, wishing, striving, valuing, achieving, *etc.*) is conceived of as a change of some state of a field in a given unit of time . . . in treating individual psychology, the field with which the scientist must deal is the 'life space' of the individual . . . it is the task of the scientist to develop constructs and techniques of observation and measurement adequate to characterize the properties of any given life space at any given time and to state the laws governing changes of these properties . . . Lewin's assertion that the only determinants of behavior at a given time are the properties of the field at the same time has caused more controversy than any of his other systematic principles. This principle asserts that the life space endures through time, is modified by events, and is a product of history, *but only the contemporaneous system can have effects at any time*," [11, Foreword]. The field or life space of Lewin seems clearly to correspond to the level variables which we here use. The "behavior" and the "laws governing changes of these properties" correspond to the rate variables.

Policy Subsubstructure

The rate equations are the policy statements in a system. They are the rules whereby the state of the system determines action. A policy statement is seen as having four components. The first is the goal of the decision-making process. It is the objective toward which this part of the system is striving. In the very broad sense used here, physical processes have goals just as do individuals in their decision making.[2] Second, the policy specifies certain information inputs on which the decision-making process is based. These are the apparent states of the system. Apparent state must be distinguished from true state. It is only the *available* information which governs a decision. A true system state may be delayed, distorted, biased, depreciated, and contaminated before making its appearance at the decision point as an apparent state. Both true and apparent states are system levels. Third, the policy describes a process for determining the discrepancy between goal and observed condition. Fourth, the policy defines a desired action which will result from the discrepancy. The preceding structure of a policy has been discussed in more detail elsewhere, [3, Chapter 10].

Comments on Structure

Some persons have criticized the industrial dynamics structure as being stylized or naive or oversimplified. Some seem to feel that the system concepts have been adjusted to fit the DYNAMO compiler rather than *vice versa.* We believe that the structure will come to be recognized as having simple elegance, universality, and a fundamental character common to a very broad range of systems running from physical devices through medicine and psychology to social and ecological systems.

Once one has come to have confidence in the generality of a system structure, that structure is a tremendous aid to organizing knowledge in a particular situation. One organizes knowledge for a purpose. The purpose may be to explain and perhaps to alter some specific mode of behavior. Without a purpose or objective there is no basis for defining a system. But once this objective is clear, he can then deal in terms of the closed boundary concept. Attempting to define the boundary focuses attention on what must be included to generate the symptoms and behavior mode of the system. Definition of the boundary is no doubt done while perceiving the next level of structure dealing with feedback loops. As the loops are defined, these become the paths through the real-life system which are to be represented in the specific model of that system. The loops represent the cross-sections out of reality which are to be recognized as important for the purposes of the particular study.

[2] The float and valve in a toilet tank have the goal of keeping the tank full. An identical conceptual structure describes a pail of water with a hole—the outflow (action) depends on the difference (discrepancy) between the water level (apparent condition) and the water level at the hole (the goal).

After establishing the boundary and the feedback loops, one begins to sort system variables into levels and rates. All variables that define the state of the system are levels and will be represented as integrations (first-order difference equations). All variables that define activity will be algebraic and belong to the class of rate equations. Levels determine rates, and rates generate levels. Any path through a system structure will necessarily encounter alternating level and rate variables. The subsubstructure within a rate or policy statement focuses attention on the concepts which must be incorporated.

After one has practice in its use, a formal, dependable, and general structure reduces by as much as two orders of magnitude the time necessary to establish the significant relationships that are buried within the conflicting, inadequate, and irrelevant information found in an actual situation.

It is perhaps unnecessary to point out that an industrial dynamics structuring has almost no relationship to the normal corporate organization chart. The dynamic system structure deals with information flows and decision points that control specific action streams. The decision stream at one particular policy point in the system may represent contributions from a number of persons or levels in the actual organization. Conversely, any particular person is likely to be a part of several different decision points controlling quite different flow rates.

The levels in an industrial dynamics model are cast in terms of first-order difference equations. Because the solution interval is made sufficiently short, this is entirely equivalent to a system of integrations. One might comment then on the choice between a system of equations cast in the form of integrations versus a system of differential equations. Engineering systems are almost universally defined in terms of differential equations. But this seems artificial. It tends to focus attention on the wrong direction of causality. For example, if one is filling a tank from a garden hose, our perception of reality suggests thinking of the water in the tank as the integral (accumulation) of the stream from the hose. The alternate statement, built around differentiation rather than integration, would define the water flow rate from the hose in terms of the derivative of water level in the tank. This derivative formulation comes close to implying that the water flows from the hose *because of* the change in water level. The differential equation formulation tends to obscure the direction of causality in systems.

One can go a step further in questioning the differential equation description of a system and call attention to the fact that nowhere in nature does the process of differentiation take place. No instrument measures derivatives. Devices which nominally measure rates of flow in fact measure average rates over some time span and operate on principles that involve integration. When a physical solution to a differential equation in engineering is to be obtained, as on a differential analyzer, the equation is first integrated enough times to eliminate derivatives. "Differential analyzer" is a misnomer; the machine is assembled from integrators.

In teaching system dynamics we have found it much easier and much more natural to the student to deal exclusively with the processes of integration and to make no reference to differentiation. Differentiation is seen as a mathematical artificiality which does not have a real life counterpart in the systems being represented.

The Task Ahead

The reader is, of course, correct if he observes that the available literature and educational materials do very little to help him achieve the understanding of systems implied by the preceding sections. The industrial dynamics literature suggests the promise of advantages which may accrue from a better understanding of systems, but it does not adequately convey the essential mathematics of the field, nor expose the principles which should guide judgment in modeling of systems, nor does it provide an adequate number of examples to be used as guides in system structuring.

If system structure and dynamic behavior are to form a thread that runs through a management education and integrates the functional areas into a cohesive whole, several gaps must be filled. There must be an appropriate treatment of the mathematics of system dynamics. There should be examples of the system structures that generate some of the principal modes of behavior seen in corporate and economic systems. There should be bridging articles to show how system concepts can be applied in the functional areas and to management policy.

Mathematics of Feedback Systems

There are now numerous books on the mathematics of feedback systems, but most of these concentrate on obtaining analytical solutions. For this reason the mathematical techniques are pressed to the absolute limit. Even so, the systems dealt with are too simple to be of much managerial interest. While concentrating on the mathematical frontier, the existing treatments do not adequately stress the simple concepts of dynamic behavior with a primary aim of improving the individual's intuitive sense of how feedback systems function. At MIT we are now embarking on an interpretation of the existing mathematics to simplify, to expose more clearly the concepts, and to make the material a base from which intuitive judgments and simulation studies can be extended.

Principles of Feedback Behavior

Besides a mathematical treatment of systems, there seems to be a need for a descriptive treatment which verbally identifies principles and illustrates these by examples. Such a treatment would depend heavily on simple problems and exercises aimed at making the concepts and the techniques part of the working skills of the student. The author is now writing such a book with an accompanying workbook of exercises.

System Examples

A person applying the industrial dynamics approach to actual corporate problems seems to do so by drawing heavily on his mental library of the systems which he has previously studied. If others are to be able to do the same, such libraries of examples must be put in orderly written form. Such a series of structures would identify those relationships which are found repeatedly in industry. [References 8, 12, and 13 suggest the nature of this approach.] Such a treatment of systems should concentrate on the minimum structure necessary to create a particular mode of behavior. Along with such an identified structure would be presented the ensemble of data which in the actual situation indicates that the particular subsystem is apt to be dominant. Historical data are often decisive in distinguishing between the possible subsystems that might be causing a corporate difficulty.

Bridging Articles

A series of articles is necessary to show how system structuring can be brought to bear on the problems that manifest themselves in various functional areas of management. Difficulties that appear in one functional area are apt to be caused by a system that cuts through several functional areas. Such articles would create ties between different fields which now are too highly compartmentalized.

Management Education

Management education has been without a foundation of theory to serve the function that physics provides to the technological professions. Although many academic programs in management treat economics as a discipline underlying management, we might better see both management and economics as systems having the same conceptual structure and exhibiting similar kinds of dynamic behavior. They differ in scale but not necessarily in nature or essential complexity. The physical size or scope of a system has but little to do with the complexity of the model necessary to represent that system adequately. The bigger the system, the greater can be the degree of aggregation. A model of an economy need not contain all component companies. A model of a company does not represent each person. A model of human behavior would not reach to the individual cell. A model of dynamics of a cell would aggregate to a much higher level than individual atoms and most molecules. In fact, the models needed in each of these systems would probably be of about the same complexity.

The nonlinear, multiple, feedback loop structuring of systems with associated dynamic principles should grow into a foundation and central core to unify management education. The same approach to organizing relationships should serve in each functional area, in economics, and in psychology. Linking between the areas would then become easy if they were cast in a common underlying structure.

As management education moves toward a greater emphasis on systems, the mathematical threads running through the academic material will change. The future will show less concentration on statistics and matrix algebra and more on the continuous variables of causal systems. There is a common foundation beneath statistics and the mathematics of continuous processes, but the two branches of mathematics seem to produce very different attitudes in students (or the paths are followed by students who previously had developed different attitudes). The branch of mathematics dealing with random events seems to be associated with a view of the world as being capricious and beyond control. The mathematical branch through differential equations (or the preferred integral formulation) emphasizes the cause-and-effect relationships and supports the attitude of an environment that can be altered and controlled. Statistics seems to concentrate on the deviation of processes from the mean, with insufficient attention to the ways of changing the mean. The approach through continuous variables lays first emphasis on the causal structure that controls the mean and, when this is understood, adds randomness to determine the influence of uncertainty on the system.

Industrial dynamics has more in common with the case study approach than with most other methods in management education. But it goes further than discussion of a case. Building a model of a process enforces more disciplined thought than does mere discussion, just as a written description usually leads to more careful thought than does a conversation. So model building leads to a better considered and more precise statement of the system description. After a model has been formulated, model simulation shows whether or not the agreed component assumptions can lead to the expected behavior. The simulation result is often not as expected. The degree to which the model behaves like the actual system that is being modelled is one measure of model validity. This check is never achieved in a mere case discussion of a management system problem.

Industrial dynamics should help fill in the management part of management education. Now much of management education serves the interests of the staff advisor but not of the line manager. The manager's viewpoint has traditionally been reserved for a policy course taken usually at the end as a capstone to a management education. But systems thinking and the ability to deal with dynamic interactions takes much longer to learn than the facts of the functional areas. In response to the systems challenge, we should expect to see a core being developed through the entire management curriculum. This core will be a new ensemble of subjects that deal with the mathematics of systems, the dynamic principles of systems, the conversion of experience and descriptive knowledge to a precise structured form, policy design through simulation experiments, coordination of model systems and case discussions, and a policy course that builds descriptively and intuitively beyond a foundation of policy studies in the form of dynamic models.

Exploration of system dynamics by way of more comprehensive models is opening the door to a new understanding of feedback processes in social systems. The future will no doubt show that we now know only a fragment of what we need to learn about the principles, theory, and behavior modes of feedback structures.

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