CHAPTER THIRTEEN

SYSTEM DYNAMICS FORECASTING IN INTERNATIONAL RELATIONS

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With the assistance of Brian Pollins

I. INTRODUCTION

System dynamics represents a theory of system structure and is a set of tools for identifying, depicting, and analyzing multiloop, nonlinear feedback relationships. It is a relatively new method of analyzing the structure and behavior of social systems, although its theoretical foundations were set several years ago by control theory and systems engineering. In its present form, system dynamics draws upon the intellectual world view now associated with general systems theory, systems analysis, and cybernetics. As a method of analyzing social systems, it was initially developed at MIT two decades ago and was first employed as a means of analyzing the management problems associated with production schedules and product distribution in industrial firms. More recently, a wider range of social and political problems have been examined through the use of this methodology, and only in the past 4 to 5 years have scholars of international relations drawn upon the underlying analytical tools for investigating global problems.

The objectives of a system dynamics study are as follows:

1. To understand the *structure* of the system under consideration;

2. To identify *policies* that might propel a system toward the desired objectives, or assist in avoiding negative outcomes;

3. To clarify prevailing *theories* regarding the system in question and provide the basis for the comparison of alternative theories;

4. To identify and resolve differences in *assump-*

tions, perspectives, and views regarding the structure or processes under consideration; and

5. To isolate *sensitive parameters* in a model whose modification would affect overall system behavior.

Given the complexities of international interactions, the frequent nonlinearities, and the difficulties of identifying, measuring, and predicting the future behavior of key variables, system dynamics as a methodology has important potential uses for the analysis of international behavior. Many of the problems confronting national leaders involve a host of factors over which they do not have direct control and whose interactions they do not fully understand. Different assumptions are made and policies identified accordingly. Yet there is little provision within conventional modes in inquiry—in either academic or policy-making circles—for systematic investigation of the consequences of alternative assumptions or of the ways in which one's analysis of a situation is shaped by the assumptions one employs. The system dynamics paradigm is extremely well suited for the organization of information, theories, and expectations regarding the problem at hand; and the accompanying algorithms allow for ready investigation of the implications or consequences of enacting alternative policies. Thus, a decision maker can define the boundaries of his problem, specify in even loose fashion the relationships among key variables, and articulate his expectations regarding their future behavior. With this information, it is then possible for an analyst to develop a formal specification of the problem at hand, isolate major interactions and feedback relations, and observe the consequences for system behavior of the adoption of alternative policies.[1]

By way of illustrating the applications of system dynamics to international relations forecasting, this chapter outlines the basic research method and underlying methodology, specifies the assumptions, biases, and perspectives, and compares these with econometric analysis, a more frequently used mode of inquiry among quantitative political scientists. Since scholars and analysts of international relations have, as yet, not been fully exposed to system dynamics, one purpose of this chapter is to provide some specific examples of the uses of this methodology for forecasting purposes, and to indicate the attendant gains and losses.

II. THE APPROACH

The most fundamental tenet of system dynamics relates to the nature of systems and to the limitations on the capacity of the human mind to anticipate the behavior of higher-order complex systems. It is assumed, first, that in all nontrivial systems, cause and effect are often widely separate in time and space. This results primarily from the fact that *delays* are present in the system structure that tend to widen the link between an action and its effect. Such delays involve information gathering, policy implementation, and policy effects. Thus, actions intended to produce one kind of outcome at one point in the system all too often result in an adverse or unintended outcome at that same point, or at some other point in the system. The inability of the human mind to trace the higher-order effects of even a singular action underscores this problem. In addition, human comprehension is thwarted by the fact that many critical relationships in systems are *nonlinear*, discontinuous, or have no adequate linear approximation. It is difficult for the human mind to incorporate nonlinear relationships into "thought experiments" or mental models, or in any kind of nonformal analysis. Finally, since the sheer number of relationships within the complex systems is overwhelming, it is extremely difficult to comprehend system behavior without recourse to formal modeling. Thus, system dynamicists argue that because delays, nonlinearities, and complexities are inherent to social systems, it is necessary to employ a computer-based simulation for understanding their behavior and for identifying the higher order and long-term effects of individual decisions or policy interventions.

The second important aspect of this approach is derived from the first. Since any formal model is superior to its verbal counterpart, our understanding of the system under study is better served if we begin formalization at an early stage, rather than wait for total conceptual closure. Therefore, the value of a model lies in its utility more than in its validity. Questions of model validity are less important than model *utility* for system dynamicists, and the usefulness of a model for policy purposes is the most important criterion for model evaluation. However, there is nothing in the accompanying algorithms that would prevent an analyst from employing rigorous validation criteria or from constructing a fully specified and deductively complete model, conformable to standards of formal validation. However, since a system dynamics model is generally formulated in terms of the search for solutions to a specific problem, its purpose is always articulated as a basic input into the model, and the level of technical detail and specification is determined by the objectives of the investigator. Thus, if his purposes were to determine and apply standards of formal rigor to his inquiry, then the algorithms would accommodate such an effort.

Third, this approach assumes that an investigator's purpose is to search for policies that would increase the probability of desirable outcomes and decrease the probability of negative ones. This leads to a research strategy of *satisficing*, rather than optimizing as is more conventionally the case with other formal modeling approaches. A key philosophical contention in this regard is that optimizing is not a legitimate activity for social modelers, in view of the complexities of interactions among components of a system and the limitations of existing analytical tools.

Fourth, it is assumed that complex systems are dominated by feedback relations. A feedback system is influenced primarily by its own internal structure involving elements related through negative and positive feedback. The behavioral tendencies of a system depend on the balance of positive and negative loops. The obvious bias is upon endogenous explanations of system behavior: A model that resorts to exogenous factors for producing system behavior is, by definition, a poor model. Thus, a system dynamics model is exclusively a *closed system*. Defining the boundaries of the problem amounts to the single most important prerequisite for developing the structure of the model, and boundary definition is predicated on an explicit statement of problem and purpose. The implications of the foregoing for simulation are fairly straightforward. Since the basic structure of a feedback loop is "a closed path connecting in sequence a decision that controls action, and the level of the system, and information about the level of the system, the latter returning to the decision-making point" (Forrester, 1968, pp. 1–7, and 1971), the model is first approximated by specifying the loop structure.

Fifth, as an outcome of the above assumptions, system dynamics is predicated on the analysis of *functional relationships* in a feedback system and not, as is common in social sciences, on the analysis of stochastic relationships. The difference in emphasis is one of interlocking feedback with nonlinear relations in a system of differential equations, versus (1) best fit criteria; (2) simultaneous solutions of algebraic equations; or (3) optimization of key parameters. But there are, again, no methodological reasons why stochastic analysis cannot be undertaken within a system dynamics paradigm or, alternatively, why the parameters of a system dynamics model cannot be derived from empirical data. In some cases, both approaches may, in fact, be complementary. However, no one has, as yet, employed both methodologies to analyze the same problem and determine the gains and losses accompanying each approach. This emphasis on functional rather than stochastic relations is predicated on the utility assumption noted above and on the desire to use a model for policy purposes. It emerges from the general policy orientation of system dynamics investigations and is a necessary consequence of the modeling approach. System dynamicists would argue that the emphasis on statistical relationships constitutes misplaced effort for modelers concerned with analyzing the implications of policy interventions in complex systems, since such systems can more readily be understood in terms of their constituent parts interacting through feedback loop structures. Efforts to develop statistical specifications of these functional relationships would deprive the investigator of the analytical flexibility brought to bear on his understanding of the system structure. This issue remains much debated among supporters and opponents of system dynamics. In the last analysis, its resolution depends on an accurate specification of the gains to be attained by focusing on stochastic relationships, in contrast to the losses of analytical flexibility incurred in efforts to meet assumptions underlying statistical analysis.

Sixth, the operational directive is for *conditional* analysis, not point prediction. Within this paradigm, accurate point prediction is not possible, although a system dynamics forecast can provide a better understanding of international behavior than a purely probabilistic model or models based on linear-additive assumptions. This is a particularly powerful perspective for analysts concerned with modalities of behavior rather than specific predictions at a particular point in time. System dynamics is thus concerned primarily with the overall behavior of a system over time; in policy testing, it is interested in finding out how policies will change system behavior, not in predicting the specific point at which the change will occur or where a system will be at any given moment.

In sum, the approach of this forecasting technique is basically defined by the following suppositions:

Formal models are necessary for understanding the behavior of complex systems.

The behavior of a system can be best understood if it is modeled as a set of *endogenous* processes.

Endogenously determined behavior is generated by *functional* relations.

Forecasting is specified in *conditional* terms.

III. THE RESEARCH PARADIGM

System Dynamics and Systems Analysis[2]

System dynamics is actually a specialized method for performing systems analysis. As such, it professes a systems-analytic ontological view as well as a systems-analytic form of problem representation. As in all systems analysis, a system dynamics study will focus its observation and analysis upon (1) those elements or variables relevant to the question at hand, (2) the arrangement of those elements and their patterns of interaction, and (3) the way in which the system transforms inputs into outputs over time; that is, the dynamic behavior of the system.[3]

In systems analysis, the elements of the system under study and their arrangement is generally referred to as the *structure* of the system, and the "rules" by which inputs are transformed by the structure into dynamic behavior define the system's *function*.[4] To avoid any confusion, it should be restated that the inputs are generated endogenously: The system is closed. In a dynamic study, the outputs (behavior) of one period become the inputs of the next period. The structure and function of the system are assumed invariant, at least over the time horizon of the study. Since both structure and function are time invariant, and system inputs result from feedback relations, the behavior of the system is said to be "state-determined." In system dynamics, structure and function are also treated as time invariant. However, the possibility of structural transformation is recognized, although not accommodated by the attendant algorithm.

Some system-analytic algorithms, such as linear programming, are structured to maximize or optimize certain values. This is not the case with system dynamics; it is not an optimizing strategy and carries no specific optimizing techniques. As noted earlier, system dynamicists are interested in the behavior mode of the entire system over time, so that long-term direct effects of various policies may be examined and unanticipated consequences may be identified anywhere in the system. The investigator's goal is to increase (rather than maximize) the probability of desirable outcomes and decrease (rather than minimize) undesirable outcomes. This, in Herbert Simon's words, is a satisficing rather than an optimizing approach.

The Structure of the Forecasting Language

The modeling language is DYNAMO, a formal representation of the system dynamics worldview, as well as a computer language to represent the system mathematically. The attendant graphical representations of the functional relations and of the computer program are key aspects of the modeling procedure, since they are designed to assist the investigator in understanding the basic assumptions built into the model.

The major elements of the modeling language are: (1) *levels,* which are the state variables in the system, the major structural determinants; (2) *rates*, which control the fluctuations in the state variables; and (3) *auxiliaries*, which help define the rates. The basic mathematical tool is integration, through which we are able to relate a quantity (level) at any given moment to the rate of change of that quantity over time. So, for example, if we think of rates as representing "decisions," then levels are the accumulation of all past decisions. In reality, rates are action streams that *may* be determined by conscious human intervention (e.g., all policies enter the system as rate changes), but may also be determined unconsciously by structural factors in the system. Auxiliary variables are actually expansions of the rate equations, and they are included as distinct entities in the system simply to assist human understanding of the relationship between levels and rates. Auxiliaries and rates may change rapidly, in comparison with levels, which change more slowly.

There are three additional elements in the modeling language: delays, table functions, and constants. Delays, essentially, represent lags in the system. They are of two kinds: material delays, representing the lags of material flows, or information delays, referring to information flows. These delays usually account for the separation in time between cause and effect. At times, delays will enhance system stability since they may dampen the effect of a "shock" in the system. More often, delays thwart system stability in that unanticipated consequences are usually caused by delays in problem recognition and policy implementation. In fact, the "overshoot and collapse" behavior mode exhibited by many systems could not occur without the presence of delays. The specification of delay structure is necessary for the investigator to formalize the temporal influence throughout the model. This consideration is crucial in forecasting, where the importance of delays in shaping behavioral responses is infrequently recognized.[5] To a very large extent, the structure of delays shapes the response of the system to alternative policy specifications.

Table functions represent functional relationships between two variables, and they are the primary means by which the system dynamicist is able to incorporate nonlinear relationships into the system. They are graphical representations of bivariate relations, and the shape of the graph provides the program with the information necessary for specifying the value of a system variable at any given moment. Like a bivariate regression, the computer will assign a value to a specified variable that is dependent upon the value of another variable (time may be used as the independent variable as well as any other variable in the system). The important feature, of course, is that this function need not be linear. Table functions can also be used to incorporate information that is not easily quantified (so-called soft variables) or to include qualitative relationships in the same manner that an econometrician would include dummy variables. Finally, constants may act as coefficients, or they may be employed as multipliers influencing other variables.

The first formal representation of the relationships is a model of the causal loop diagram; but it does not distinguish among levels, rates, auxiliaries, or delays. These distinctions are made in the DYNAMO flow diagram and become the necessary precondition for writing the equations. It is always better to have as simple a representation of the processes modeled as possible. The more complex the model, the more difficult it is to understand its behavior or to gain a grasp of the dynamic processes. Generally, complexity is proportional to the number of state variables in the system, so the more levels that a model includes, the more difficult it is to understand its behavior. This emphasis on understanding is predicated on the concern with evaluating policy alternatives, for unless one understands the structure and behavior of a model, it is not possible to assess the relative implications of alternative policies.

Procedure

A typical system dynamics study is composed of ten stages with interactions back and forth:

1. Become familiar with the issues to be modeled and obtain an understanding of the system in question, delineating the issues and problems;

2. Provide a verbal description of the general question or problem to be addressed, specifying the endogenous, exogenous, and excluded issues;

3. Identify the reference mode of the system, that is, the dynamic behavior one would wish to model and reproduce initially as the first formal representation of the issues of concern;

4. Specify the system boundary, delineating endogenous, exogenous, and excluded variables and relationships;

5. Formulate the causal loop diagram representing the structure of the system, and the basic mechanisms believed to cause the reference mode specified in the previous stage;

6. Formulate the DYNAMO flow diagram as an unambiguous graphical specification of the system structure;

7. Write the DYNAMO equations, that is, the program input into the computer;

8. Examine the computer output, noting the model behavior for changes in the structure or in the parameters and undertaking systematic experiments with alternative policy runs to understand the behavior of the system in cases of different policy interventions;

9. Provide additional detail in the structure of the model until it is sufficiently realistic to meet the needs of the user; and

10. Make policy recommendations based on the results of the sensitivity runs.

The construction of a causal loop diagram (stage 5) is the first step in transforming a verbal and intuitive understanding of system structure into a formal representation. It specifies how the elements of a system fit together and the direction of the influences. It is the initial formal representation of the positive and negative feedback loops. The DYNAMO flow diagram (stage 6) then specifies the model in terms of its constituent elements: levels, rates, auxiliaries, and delays. And the development of computer (model) equations follow formally from the detailed DYNAMO flow diagram. These equations enable the investigator to undertake stages 8 and 9 in the development of a system dynamics model.

So far we have described the research paradigm underlying system dynamics, the basic assumptions, methods, and procedures, and structure of the computer language. At this point, we compare the key assumptions of system dynamics with those of econometrics. Our purpose is to identify the convergences and divergences between these two modeling traditions, by way of evaluating the gains and losses of each.

IV. A PARTIAL COMPARISON OF ASSUMPTIONS: ECONOMETRICS AND SYSTEM DYNAMICS[6]

Our comparison revolves around several generic issues at the base of all computer modeling techniques:

System Boundary

Econometric models are *open* systems, including many factors that are, relative to the time horizon under consideration, not determined by the system modeled. Furthermore, econometric models make necessary use of exogenous variables in order to estimate the parameters of the model. But there are specific assumptions about the nature of these exogenous variables, and restrictions on their use. By contrast, a system dynamics model seeks to represent a *closed* system. Its objective is to generate reasonable system behavior without recourse to exogenous variables. It is assumed that if all the key relationships have been included within the feedback loops, the phenomenon modeled will be adequately explained.

The Role of Stochastic Factors

Econometric models assume that a forecast is not meaningful unless accompanied by a statement regarding level of uncertainty, and that the error around the parameters estimated from empirical data provides information regarding the reliability of the forecast. Again, by contrast, a system dynamics model does not take account of random factors, but it assumes that these are not strong enough to determine system behavior. Since the purpose of a system dynamics model is to isolate the impact of key policies, delineating the effects of stochastic factors is not considered important. An econometric model, however, makes use of the information contained in the level of uncertainty and in the disturbances or residuals.

Validation

Econometric assumptions adopt a statistical perspective on validation, where conventional statistical criteria are employed to determine the significance of individual equations and their correspondence to empirical observations. The criteria are external to the model and do not depend on the purposes of the investigator. By contrast, validation in a system dynamics perspective is almost exclusively determined by the extent to which the model replicates historical behavior, even on face value, and assists in understanding a specific situation, or is useful in making decisions about a real problem. Validation is relative and there are no external criteria by which to judge the validity of a model other than its usefulness for policy analysis. (There are other ways in which validation is regarded, but they are not critical here.)

The Uses of Data

Econometric models require data to estimate the parameters and to evaluate the validity of the model. Without data, the model cannot be tested. Access to data is critical for any econometric model. There are conventional data requirements and constraints and established procedures for evaluating their characteristics and the extent to which they can be used for estimation purposes. On the other hand, in a system dynamics model data does not assume the paramount role that it does in an econometric one. It is believed that there are too many nonmeasurable factors of importance, that data cannot represent the dynamic attributes or a system; that the length of time for which a model is run is usually too short to rely profitably on the information contained in data; and that specifying functional relations among variables is more important than seeking to identify their statistical relationship. Data are often inadequate for identifying functional relations. This is to suggest, not that a system dynamics model does not make use of empirical information, but that the observations employed are not required to meet the strict requirements posed by econometric and statistical models.

Reference Mode

The reference mode is the historical behavior of the system under study, or the future behavior mode of the system that the researcher would like to duplicate. By replicating historical behavior, we validate the model. By replicating the desired future behavior mode, we find the correct policies. For pragmatic purposes, it is useful to specify the desired future behavior in terms of an equilibrium condition. The policy exercises, therefore, identify the options that would contribute to this outcome or to any specified alternative. An econometric model does not rely on comparing alternative policy runs with the standard run. While this is often done in practice, it does not assume the same importance in the research design.

Time Frame

Most uses of system dynamics adopt a long-range perspective on the problem modeled; it is generally assumed that only a long-run perspective will yield full evidence and insight into the behavior of the system and its characteristics. In an econometrics model, by contrast, it is customary to focus on the shorter range, largely on the assumption that the parameters estimated from empirical data are valid only over a short time period, and that changes in the system result in parameter changes that may invalidate the initial models used for economic planning require a short time horizon to be maximally useful. The difference in perspective results from the practices of the modelers, and not from any built-in requirement or attribute of the methodology. The algorithms of system dynamics can adapt to any time perspective with any time interval. The same is generally true for analysis.

Feedback

The system dynamics model is, most centrally, based on interlocking positive and negative feedback. Dynamic processes are built into the model—by assumption, algorithm, and functional specification. Econometric models are generally less dynamic and less prone to feedback specifications. This is due in part to the nature of the algorithms, and in part to established practices in the field.

V. APPLICATIONS TO INTERNATIONAL RELATIONS

Few scholars of international relations have, as yet, drawn upon system dynamics for either modeling or forecasting purposes. At this point, we summarize some recent efforts in this direction, by way of illustrating the general uses of this methodology, and attendant problems and prospects.

Two examples will be employed, both drawn from recent investigations on the international implications of resource problems undertaken at the Massachusetts Institute of Technology. A third example will be reported on more extensively in

Chapter 21 (p. 308). Suffice it here to illustrate the general approach and the attendant gains and losses. The three studies represent different stages of a research program in international relations forecasting, the empirical investigations of which were supported by a grant from the National Science Foundation. The basic purpose of this research is to understand how a nation's resource endowments shape its foreign policy behavior, and to test the implications of different policies pursued to assure access to resources. A second objective is to determine the conditions under which various policies might be conducive to international violence, and to determine the responses that would decrease propensities for conflict among nations.

The first study represents a general statement of the relationship between resource endowments and foreign policy and presents some initial policy runs. The second study is an examination of the policies and interactions of petroleum exporters and importers in their attempts to develop means of meeting their respective foreign policy objectives. The third study is a more detailed analysis of the domestic sources of external behavior and of the role of resource scarcity in the calculus of determinant variables, with the United States as a specific case study.

The following sections of this chapter describe each effort briefly as a means of illustrating the ways in which system dynamics has been, and continues to be, a useful tool for international relations forecasting.

Resource Scarcity and Foreign Policy: A Simulation Model of International Conflict[7]

This model represents the first application of system dynamics to international relations. Its purposes are to formulate a generic structure of interactions among the various determinants of foreign policy behavior, to isolate the factors that shape a nation's resource needs, and to identify the policies that could assist in meeting these needs. A basic concern is to determine how different policies could be conducive to international conflict. The basic theory adopted for modeling purposes is predicated on the proposition that major wars often emerge by way of a two-step process: In terms of internally-generated pressures toward expansion of interests and in terms of the reciprocal comparisons, rivalries, and conflict for control over resources or valued goods, territory, or spheres of influence. Each process tends to be closely related to the other and each, to a surprising degree, can be accounted for in terms of more aggregate considerations or variables that are relatively state determined or nonmanipulable in the short run.[8] For this reason, it is important to find out what variables policy makers can, in fact, manipulate and what effects such manipulations might have on the behavior of a system.

The model is composed of a set of feedback relationships representing the demands for resources generated by a growing population with military and economic capabilities to pursue these demands through various modes of international behavior. The more pressing the demands, the greater will be the pursuit of external sources, particularly if resources are not available domestically, or if they can be obtained more cheaply elsewhere. Conflict is modeled as occurring when two or more countries with high capabilities and unsatisfied demands extend their activities outward and increase their allocations to the military in pursuit of such activities. The problem, thus, is to find policies that would ensure access to needed resources, while at the same time decrease external violence.

The forecasting model is composed of several distinct but interrelated sectors, each composed of one or more feedback loops, and connected through a series of loops. These sectors are: (1) population, determining the demands on resources, and demands for productive capital to assist in pursuing resource needs; (2) productive capital and technology, to yield the relationships generating capabilities to pursue resource demands; (3) domestic pressures, representing the outcome of the interaction between population, resource needs, and productive capital; (4) military expansion, representing the effects of allocations to the military; and (5) resource usages and allocations, representing the acquisition of external resources and the extent to which such acquisitions detract from the exploitation of internal sources.

The types of policy options investigated included behavioral alternatives available to a nation as it seeks to attain its foreign policy goals, as well as inputs into the decision system of a nation occasioned by the actions of other states. Thus, we looked at the impact of the decision to refrain from exploiting domestic resources and to rely exclusively on external sources, and observed the implications for the behavior of the system. Our analysis suggests that such a policy would result in increased foreign costs, as well as increased allocations to the military, both of which would necessitate drawing excessively upon available productive capital, and channeling it to resource acquisition activities rather than to economic growth. The long-term impact would be to reduce the availability of productive capital. Alternatively, we investigated the consequences of a policy of refraining from employing external sources and focusing specifically on domestic resources, and observed that the net effects depended largely on the initial level at which the domestic resources of a nation were specified. In the prototypical US model specified as having a relatively high resource base, such an option would not have negative effects economically, and would avoid accelerated investments in the military, and, by extension, detract from diverting productive capital to nonproductive uses. In still another set of policy runs, we set up the forecasting problem so as to reflect a situation in which the United States would be faced with low internal and external usable resources and high foreign costs of acquiring these resources. Any policies designed to increase the availability of resources in such a context would result in the initial increases in consumption per capita (reflecting a situation before the full impact of foreign costs were incurred), but then consumption would fall off (indicating the constraints encountered). In the longer run, however, declines in consumption per capita will have positive effects, enabling increases in subsequent investments available for expansion. With a persisting shortage of resources, the overall behavior of the system exhibits a gradual decrease in expansionist propensities and in foreign policy activities.

These broad observations are designed to indicate how a problem in international politics can be defined in system dynamics terms, and the kinds of issues that can be fruitfully investigated. This first study has led to a clearer specification of the foreign policy problems associated with the desire to gain access over scarce resources. The second study, referred to above, represents a continuation of this effort. Its purpose is to be of assistance to foreign policy analysts concerned with United States policies toward the exporters of its raw materials.

Energy Demand and International Politics: Imports, Price, and Costs[9]

The extension of the forecasting work described above focuses on the problems to be encountered by the United States in the next 30 years in its attempt to meet its petroleum needs. We begin with the fact that the United States is the world's largest producer of energy, but also its largest consumer, and, being a net energy importer, its economy is increasingly vulnerable to disruption by international factors. Even with the stipulations and policy directives of Project Independence, and its favorable resource/consumption position in relation to other advanced industrial societies, the United States will not become self-sufficient by 1980 or even 1990. Policies designed for self-sufficiency, if implemented today, will not reduce the United States' dependence upon external imports in the immediate future. The country will continue to face the same problems confronting other consuming states.

The complexities of interdependencies between petroleum exporters, the importing countries, and the multinational oil companies who manage petroleum exchanges require a model that takes into account the international determinants of economic and political costs of meeting resource demands with attendant sources of conflict; enables analysis of the consequences of potential policies of and for both producers and consumers; assumes a global perspective by taking into account constraints upon the physical process of resource production; and assists in identifying potential long-range impacts of immediate decisions.

As presently structured, the model is strongly influenced by the difference between domestic production and consumption. The demand for petroleum affects the consumer's trade balance and overall balance of payments; this balance is also influenced by the extent to which the producers pursue policies of increasing repatriation of overseas investment profits. The greater the repatriation, the more positive the effects on the country's balance of payments, but the lower will be investments in expanding the availability of overseas resources. Thus, there are clear trade-offs identified from the consumer country's perspective. For the producer countries (whose policies and decisions inevitably affect the consumers), investments, tax rates, patterns of resource consumption, and imports of commodity goods from the consumer countries are all determined by development priorities and by accumulation of capital stock. The producer's long-term capital investments in the consumer countries will offset the latter's capital account. Thus, to the extent that the producers choose to repatriate investment income, they directly influence the consumer's balance of payments.

This series of interactions provides the structure of the model and enables us to examine the consequences for the consumer countries of various investment and tax policies enacted by the producers, and vice versa. The application of system dynamics to this kind of behavioral problem in international relations is very useful in assisting foreign analysts to identify potential outcomes of alternative policies. It is also of assistance to identify the types of policy experiments and forecasting runs that would be helpful for thinking about the future implications of alternative US postures in interactions with the producers of crude petroleum.

This forecasting project was completed in the winter of 1975. The modeling activity is structured to take account of the flows and interactions among producers, consumers, and the investment activity of the multinational oil corporations. It incorporates the international financial consequences and the flow of revenues across national boundaries as consumer countries seek to find means of meeting their oil import payments; it takes into account the decision processes within the producer and consumer governments, and the decisions governing investments in exploration and development of petroleum sources. The first forecasting goal is to reproduce the historical behavior of inte actions between producers and consumers; the second is to determine the effects on each of the policies adopted by the other.

A third forecasting study employing system dynamics to examine an international relations problem is described in great detail in Chapter 21 of the present volume, where we present specific forecasts and analyze their implications. This study is a systematic attempt to examine the implications of alternative US government priorities upon the disposition to extend national behavior outside territorial boundaries. As such, it represents a partial theory of the sources of foreign policy, specifies the functional relationships among constituent elements in the theory, and examines the implications in terms of alternative futures for the United States.

NOTES

1. Further along in this chapter, we shall present specific examples of the foregoing.
2. The material under the heading "System Dynamics and Systems Analysis," Section III, was written by Brian Pollins. The purpose of this section is simply to acquaint the reader with the relationship of system dynamics to systems analysis, a more widely known research paradigm. It is not an exhaustive discussion of the issues involved.
3. The observations on systems analysis in this section of the chapter are drawn largely from Cortes, *et al.* (1974), p. 336. This book is an excellent introduction to systems analysis as a research paradigm, and is written for the nontechnical reader.
4. Despite the terminology, this method is not similar to the "structural-functional" analysis that pervaded the early literature in the field of political development.
5. Witness the fact that the impact of delays are not examined in other chapters.
6. I am grateful to Peter Senge for long discussions on this issue and for describing the results of his experiments. This section is based on a table prepared by Senge, designed to juxtapose the assumptions underlying these two approaches to modeling complex systems. See Chapter 12 for some key elements of econometric analysis.
7. Choucri, *et al.* (1972), p. 81.
8. A detailed theoretical statement with accompanying empirical referents and analysis is presented in Choucri and North (1975). See Part II for an historical analysis and Part III for quantitative investigations.
9. Choucri and Ross (1975).

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