SYSTEM DYNAMICS:

A TOOL FOR BROAD POLICY ANALYSIS

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ABSTRACT

Industrialized societies are presently characterized by rapid change, strong interactions, and an abundance of new phenomena. To increase the likelihood of policies having the intended effects, there is a need for policy analysis with a broader perspective and longer time horizon. The main task in such broad policy analysis should be to integrate the vast amount of available information into a useful conceptual structure of the problem area.

System dynamics (SD) -- relying heavily on descriptive information for a data base, on a theory of the structure of social systems for theory formation, and on computer simulation for relating structure to behaviour -- offers one method of attaining such broad policy analysis. This paper reviews the historical development of the field and examines the major system dynamics literature. The impatient questions of "what is?", "why does one do?", "when should one do?", and "how does one do SD?" are all answered in summary fashion.

Within the system dynamics profession, intense conflicts abound as to what constitutes "proper procedure" for the policy analysis process, particularly concerning model conceptualization and testing. Much disagreement arises from implicit differences in modeling objectives. Explicit recognition of objectives and procedures could reduce much of the conflict.

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THE NEED FOR A SYSTEM'S VIEW IN POLICY ANALYSIS

Compared to past societies, today's industrialized societies are characterized by

- rapid change, so that problems grow critical more quickly;
- strong interactions, so that an action often has unintended "side" effects and "solutions" simply shift the problem to another sector (for example, from the technical to the social sphere; and
- new phenomena, so that traditional concepts and explanations, normally supported by available statistics, become less reliable. Other variables and mechanisms, not previously quantified, are needed for a complete understanding of the new symptoms (for example, stagflation).

When developments are rapid and strongly coupled in addition to being new to the decisionmaker (be it an individual or a group), policy making based on a conventional short-term and narrow perspective is less likely to achieve the intended results. This policy shortcoming characterizes both the individual organization, which must adapt to (or attempt to control) a constantly changing environment, and national institutions, which attempt to regulate the unruly development of the societal environment. Improved policy would result if the perceived problem and contemplated responses could be seen in a larger and richer context, both in time and space. The need is pressing although the result from such policy studies would necessarily be less precise and final than the "answers" in traditional problem solving. In this paper the effort to study options and design improved policy under today's fluid conditions will be termed broad policy analysis.

REQUIRED CHARACTERISTICS OF METHODS FOR BROAD POLICY ANALYSIS

In contrast to traditional approaches, broad policy analysis must emphasize:

- a long time horizon, not limited to the conventional planning horizon in industry and government of less than five years, but long enough to encompass the period influenced by current decisions and to anticipate future undesired effects in time to avoid them;
- a wide perspective, not limited to one sector or one discipline, but including all the variables and social mechanisms bearing on the problem; and
- a flexible conceptual framework, not unnecessarily limited to traditional variables, but based on open-minded observation of the real world and on willingness to define new concepts to avoid excessive emphasis on what is already measured or easy to measure.

The frequent calls for long-range planning, interdisciplinary research, and technology assessment verify the existence of an unsatisfied need for policy analysis with the suggested characteristics.

The main problem in broad policy analysis is not the lack of information, but rather the opposite. Although comparatively little knowledge about social reality may actually be available in the form of statistical compilations, a vast amount of information and tentative generalizations is accessible in written literature and in the mental models of practitioners (that is, the intuitive impressions of practicing decision-makers and experienced real-world actors). The main obstacle to a productive perspective on a problem is the difficulty in extracting from the bewildering array of seemingly relevant bits and pieces of knowledge a consistent structure of social, economic, cultural, and physical forces that interact and generate the behaviour of interest. Particularly when new problems are studied in a new perspective and with an unfamiliar time horizon, there tend to be a paucity of fruitful concepts and established theory that can help reduce the confusion imposed by, and bring order to, the ocean of disjunct details. The major requirement of a useful method for broad policy analysis is that it be able to create "good theory" to explain the causes of the problem at hand. Policy-makers need guidelines for conceptualization.

The conclusions (new insights, policy recommendations) of broad policy analysis will typically be of a qualitative nature. Still, quantitative methods are often useful in the study process. Formal methods require explicit assumptions and eliminate logical flaws in the derivation of consequences.

Useful methods for holistic policy analysis should also facilitate:

- dynamic analysis, because few variables remain constant over the long time horizon of interest in most policy questions;
- generation of alternative scenarios, because policy analysis should not primarily seek to predict specific future events, but should instead clarify the trends that are amplified by activities of interest;
- use of descriptive information, because most knowledge about social systems is not available in the form of statistics, but instead takes the form of verbal understanding, and because current understanding of social phenomena often is insufficient to warrant very detailed description; and
- ease of communication, which increases the analyst's capacity to employ practicing decision-makers as sources of information and increases the credibility -- and, therefore, the utility -- of the study in the eyes of the user.

Traditionally, efforts at broad policy analysis were best satisfied by verbal discussions: board room exchanges, parliamentary hearings, historical research, white books, and scenarios. The post-war period has witnessed a variety of attempts to develop formal methods, such as programming, econometrics, and simulation. So far, practical gains have been greater in the control of tangible, easily-measured processes than in the illumination of qualitative, long-term options. One challenge is to develop methods that do not impose inflexible limitations on the description of reality, and therefore give a better impression of precision in that description.

S Y S T E M D Y N A M I C S A S O N E R E S P O N S E

The system dynamics (SD) approach is one technique for broad policy analysis. The formal product of the approach is dynamic simulation models. SD models are (ideally) established in accordance with a specific theory of the structure of social systems, and through a process of extensive interaction with practitioners and users. As with most model building, the ultimate objective -- in the system dynamics case, increased insight into the dynamics of social systems -- is attained as much through the modeling process as from the final model.

The power of the SD approach lies in its capacity to structure available knowledge about a problem. Unessential information is eliminated by:

- relying on the filtering and synthesizing capabilities of the human brain to help identify important causal relationships;
- perceiving social reality as a state-determined, information feedback structure in order to help identify circular loops of cause and effect that influence the problem of interest; and
- confronting the mental models of different experienced practitioners in order to help select the major feedback loops underlying the problem of interest.

In the wide spectrum of formal methods for policy analysis, which parallels the spectrum of systems analysis techniques, SD is a complement to precise, decision-oriented operations analysis techniques. SD analysis seeks qualitative conclusions about policy impacts.

The SD method was developed in the late 1950's by J.W. Forrester and his colleagues at M.I.T. The first application were directed toward dynamic problems in industrial corporations -- problems related to product ordering, investment, and resource-allocation policies of the firm (see 1 - 5 in the bibliography). A continuing stream of SD policy analysis for the individual firm or organization has emanated from universities and from at least one consulting firm specializing in corporate applications (see 6 - 9 in the bibliography). The late 1960's saw the first SD studies focusing on problems of a wider societal nature -- including analyses of the decay of mature cities, the economic development of a resource-constrained region, growth in drug abuse, the adjustment of global population and industrial growth to the globe's carrying capacity, and the transfer of health care and other services (see 10 - 19). More sporadically, the SD approach has been used to elucidate the structural basis of dynamic phenomena in ecology, physiology, and biology. Other ongoing activities involve the study of national economic development and energy policy (see 20 - 21). Policy analysis of societal issues -- characterized by multiple contradictory goals, diffuse problem definitions, and grossly imperfect knowledge of the central variables and interactions -- appear to be the most promising area for future SD applications. In contrast to the literature on SD applications, publications centering on the SD method are rare (see 22 - 26).

THE SYSTEM DYNAMICS METHOD

The preceding discussion describes in general the requirements of broad policy analysis and the policy capabilities of system dynamics. The following presentation attempts to provide more concrete answers to such unavoidable, impatient questions as:

- What is system dynamics? (that is, what characterizes the SD approach?)
- Why do system dynamics? (what final objectives does the system dynamicist seek?)
- When should system dynamics be used? (in what situations is the SD approach likely to be efficacious?)

A complete answer to these questions could be obtained only through a thorough examination of the SD literature describing completed analyses and their conclusions, by actually working with the method in numerous applications, or by extensive conversation with SD professionals. The following attempt at synthesizing the characteristics, final purpose, and areas of utility of the SD approach is inevitably general and, therefore, perhaps sterile due to the wide applicability of the method. Moreover, the answers are sufficiently general to apply not only to SD, but to any other effective method of broad policy analysis.

What characterizes the SD approach?

Explorations of different possible developments

SD studies focus on patterns of development over time. One objective is to understand the forces causing specific, observed (or anticipated) developments. Another objective is to gain insight into how different actions accentuate or damp out behavioural tendencies implicit in the system structure. The objective is not to predict in detail what development will actually take place. Instead, the idea is that exploration of various possible (but often unlikely) developments introduces increased richness in the discussion of goals; the improved insight about the effects of system changes under extreme as well as normal conditions then enhances goal effectiveness and consistency in policy.

Use of extended time horizons

What is "long-term" depends on the problem focus. A study is "long-term" when it covers a period longer than required to significantly affect the development of interest. One year is long-term for problems of inventory adjustment, while ten years is not necessarily long-term for examining societal value change. In SD analysis, problems occupy a time frame long enough to encompass the full "life cycle" of the development of interest. Only on this extended time scale are fundamental behavioural tendencies likely to undergo changes.

Use of wide system boundary

Fewer variables remain constant when the time horizon is extended. To understand (that is, to have a theory for) long-term development, the main causes of change in a wider selection of variables must be identified. To achieve such an increased understanding, SD analysts seek to minimize reliance on exogenous explanations of change. As a result, SD analyses typically contain an explicit description of an uncommonly broad set of social mechanisms, including (whenever they are important) forces that are not readily (nor easily) measured. Ideally, the system boundary for any given analysis would include the full set of mechanisms necessary to generate significant variation in all important variables over the extended time horison.

Why are SD studies performed?

To establish a focus for attention

By sifting out one specific development for study, more attention and discussion is inevitably attracted to this phenomenon, thereby increasing the chance for acknowledgement and solution of the problems associated with the development. SD studies are designed to highlight specific problems of a dynamic nature and to channel resources toward their solution.

To establish a clarifying framework for discussion of policy

At first glance, a problem area often seems to present a bewildering multiplicity of diffuse, interacting cause-and-effect relationships. Policy analysis helps to structure and clarify the relevant slice of reality by selecting a useful perspective and level of aggregation for description of the problem, by identifying the important causes of development (circular cause-and-effect mechanisms) from the jungle of cause-and-effect, and by defining

the concepts necessary to describe these mechanisms. The resulting theory is then arranged in a consistent causal structure which can be used as a framework for pursuing possible solutions. Of course, the inevitable danger of establishing a misleading framework is always present.

To illuminate policy options

Although SD analysis emphasizes the continuity of and inertia in the development of social systems, the future is seen as changeable through deliberate action. Illumination of a wide spectrum of possible futures reduces the risk of automatic, conservative continuation along current trends as if they were the only available choices.

To identify surprising effects

Social systems often exhibit surprising responses to policy as a result of unanticipated interactions among the direct effects of an action. Such interactions normally turn out to be obvious, but typically only <u>after</u> they have been observed (either in the real world or in a model). SD analyses aspire to early identification of surprising interactions and to flawless accounting of simultaneous dynamic processes. Although no one can ever anticipate <u>all</u> surprises, it is still useful to discover one more surprise ahead of time.

To concretize long-term global consequences of action

Policies are often less than perfect because the time horizon of individual decision-makers is too short or because they only consider a narrow sector. Since this deficiency may be unconscious, the long-term and global consequences of current actions can be made more tangible through a formal model. Making the far future and the periphery more tangible increases their leverage in policy making.

When is SD of special use?

When there are multiple, simultaneous effects

A single action often has several simultaneous effects. These effects may in turn themselves interact to further obscure the total result. Through explicit structuring and accounting, SD analyses shed light on the total result (not losing sight, however, of the axiom that perfect knowledge about the total effects of an action in a social setting is unattainable). Formal policy analysis reduces the risk of disregarding the individual effects or the interactions between effects of a problem.

When there are delays

Situations characterized by delays between action and observable result tend to breed successive periods of overreaction and underreaction. By describing both long-term and shor-term effects in the same framework, long-term effects get more attention and therefore become more influential in decision-making. Formal policy analysis becomes in itself a feedback signal that adjusts current action so as to insure a better match between the actual future states and desired states.

When there are "irreversible" choices to be made

Certain situations prohibit or do not lend themselves to continuous re-evaluation and revision of a decision. Such decisions include those involving large population groups (for example, birth control policy) and capital investment decisions that tie up development for the life of the physical capital. Such situations warrant particularly thorough policy analysis of possible consequences of policy alternatives.

When the "tragedy of the commons syndrome" prevails

In certain situations, rational behaviour by individuals has undesirable

results for the social group as a whole. To improve the group situation, boundary conditions under which individuals make their decisions must be changed. SD analysis can help devise the new system structure necessary for the sum of individual decisions to add up to a desirable development.

How does one perform SD studies?

The question of how to proceed from first contact with a chaotic situation to reasonable security with a productive policy is the general topic of this volume. In arrogant brief, the answer to the how question consists of the following procedure: identify a problematic development; determine the underlying causal structure; identify changes that improve the behaviour of the model system; evaluate the transferability of policy recommendations to the real world; implement.

BEST PROCEDURE DEPENDS ON OBJECTIVE

This volume attempts to describe how to carry out an SD study. Policy analysis, as discussed here, consists of two stages: theory formation (problem definition and conceptualization) and model construction (formulation of the theory in a mathematical model). Both theory and its representation in a formal model evolves in a gradual, iterative way toward more germane and accurate versions. The process is guided by continuous testing (or evaluation) of the current theory or model.[1] The volume emphasizes conceptualization and testing procedures. More precisely, the volume discusses these procedures -- both the individual steps and their combination into a process. Conceptualization and testing are in fact the subject of serious dispute about what represents "proper (= productive) system dynamics practice". Much dispute probably reflects the novelty of the SD approach. An insufficient number of studies have been carried through to test all procedures and to establish a conventional wisdom concerning the best approach. But some differences in opinion about best procedure have a less visible cause, namely unmentioned nuances in objective.

The statement that "best" procedure depends on what one seeks to achieve is trite. Recommendations concerning procedure always change with variations in the objective. This principle would be irrelevant if objectives were always the same, or if best procedure were inelastic in the face of perturbations in objective. Neither seems to be the case. There is a wide -- and surprisingly unattended -- spread in modeling objectives. First, there is a difference between conducting policy analysis to achieve a product (for instance, a model or an optimal policy) or to exploit the educational content of the process (for instance, a confrontation of the mental model of the practitioner and the formal model of the analyst). But, even within the product and process options, there is room for significant nuances in objective and therefore for nearly endless disagreement about proper procedure.

To merely suggest the large extent of potential disagreements arising from unmentioned differences in objective, the following list presents a selection of commonly sought model characteristics:

- Insight generating capacity. Does the model increase understanding of the modeled system? Does it improve the mental models of the model builders or the model clients? Does it produce surprising effects that are obvious after the fact?
- Descriptive realism. Do the model components and equations represent the real system in a form that corresponds closely to how persons experienced with the system perceive it? Does each parameter or element have a readily perceivable or conceivable real-world equivalent?
- Mode reproduction ability. Can the model produce important modes of dynamic behaviour observable in the real system, under the same conditions that produce such modes in the real system?

- Transparency. Is the model easily understandable even by a nonprofessional audience? Does the model highlight the essential structure of the real system in an accessible way?
- Relevance. Does the model address problems viewed as important by experienced persons in the real system?
- Fertility. Does the model generate new ideas, new ways of looking at the problem, new experiments, or new policies that might have been overlooked in the absence of a model?
- Formal correspondence with data. Does the model incorporate real world observations embodied in standard data sources, and can it reproduce under historical conditions a reasonable statistical fit to historically-observed data?
- Ease of enrichment. Can the model be altered to incorporate new findings or to test the effects of new policies not under consideration when the model was made? Can the model be adapted to represent systems related but not identical to the system originally represented? Can the model be updated without repeating all the work that went into its creation?
- Point predictive ability. Can the model produce a precise prediction of a future event or of the future magnitude of important elements in the system?

Clearly, such a varied array of possible modeling objectives provides ample space for disagreement and misunderstanding. In an attempt to determine and emphasize the SD choice of objective -- or at least to establish a written basis for further discussion and future crystallization of proper SD objectives -- a full 25 per cent of this volume is devoted to the question of objectives, and to the paradigm foundation underlying a particular choice of objectives.

FORMAL MODELS: TWO DANGERS

The end product of most policy analyses is a mathematical model representing some segment of the real world. But formal models are accompanied by two dangerous side-effects.

Misinterpretation of results, because all formal models are assumed to be based upon the same objective.

Since models can be made for various purposes, there is a risk that they may be put to other uses than first intended. Currently, laymen and professionals both have a strongly engrained belief that mathematical models of social phenomena serve the sole purpose of precisely predicting future events. But SD models are not made primarily for point prediction. Instead, they are designed as insight-generating policy analysis tools. Still, an SD model takes the form of a complex set of mathematical equations with the accompanying aura of ability to foretell the future. This conflict between aura and intention confuses the model user, who does not have in hand the tool he thinks he has, and misrepresents the system dynamicist, who is constantly attacked for "unprofessional" behaviour judged unacceptable in the search for precise prediction, although he is not actually trying to accomplish any feat of fortune telling.

Development of an unduly influential elite basing its power on the computer mystique.

The danger of further concentration of power is discussed by Robinson and Meadows.[2]

"Like any new technology, computer modeling of social systems offers progress accompanied by danger. Because this technology concerns the processing of use and information and promises to expand the power not of human muscles, but of human brains, the bargain is doubly treacherous. On the one hand, the proper use and development of this tool could bring about a blossoming of new insights about the design and management of social systems, a clarification of assumptions and conclusions, an opening of the decision-making process to a wide variety of ideas and opinions. On the other hand, it could reduce the policy arena to a muddle of jargon and complexity, and generate a new kind of unaccountable political power -- a monopoly on the information about the future:

> Previously, it seems to me, we have had two groups of persons in secret government: the circle of scientists who are knowledgeable about what is happening and which decisions must be made, and the larger circle of administrators and politicians to whom the scientists' findings have to be translated. My worry is that introduction of the computer is going to lead to a smaller circle still ..... We shall have a tiny circle of computer boys, a larger circle of scientists who are not familiar with the decision rules and are not versed in the new computer art, and then, again, the large circle of politicians and administrators .... I suspect that the chap standing next to the machine, who really knows how it makes decisions, and who has the machine under his command, is going to be in an excessively influential position." 3

Both dangers are reduced when formal models are taken for what they actually are: explicit representations of mental models, nothing more, nothing less. This perception can be enhanced by reducing the use of inaccessible symbolism to a minimum, for instance by replacing all mathematics with readable graphics, and even better, by presenting <u>and defending</u> all study conclusions in plain language. A final stab at the unreachable aloofness of the computer analyst could come from general public recognition of the artistic, subjective nature of formal modeling. Modeling is far from a "hard" science.

Hopefully, this volume will help to reduce the dangers inherent in conflicting or misunderstood modeling objectives, and in the computer mystique.

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