

# The Use of Structural Modeling for Technology Assessment

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## ABSTRACT

Structural modeling (SM) techniques are a set of geometric, semi-quantitative tools that can assist in organizing a technology assessment (TA), developing a rough overview of it, and analyzing various component problems. In this project about 100 SM techniques were identified and seven were tested in detail: ISM, ELECTRE, SPIN, KSIM, QSIM, IMPACT, and XIMP. Guidelines were developed to help the assessor in the choice and proper use of such tools.

*Everything which is simple is false, everything which is complex is unusable.*

Paul Valery

*Man is a frivolous and incongruous creature, and perhaps, like a chess player, loves the process of the game, not the end of it.*

Feodor Dostoevski  
*Notes from Underground*

## Introduction

Structural models constitute a genre of analytic models which highlight the geometric, rather than algebraic, features of a system. They describe form and structure, rather than calculating or measuring quantitative output. They reflect Kane's assertion that structure is far more important than state for determination of the behavior of a complex system [1, pp. 140, 141]. Structural models provide a sense of the "geography" of a complex system, a rough map which can shed considerable light on the potential consequences of links between system elements. They fit the notion of modeling expressed by Holling and Goldberg [2, pp. 22, 24]:

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We would rather be roughly right about a whole system than precisely right about a trivial part of that system. . . . A model that can be probed and explored in a simulated world . . . becomes an evolving device of self-instruction. Its value is not so much to give answers as to generate better questions: not to define policy, but to expose some of the consequences of alternative policies.

For our purposes we shall define as a structural model any model which 1) represents a complex system as a set of elements with relations—nearly always pairwise—linking some or all of them; and 2) places the emphasis on the geometry or structure rather than on quantitative aspects of the relationships. It is often graphically depicted by points (or nodes) and connecting lines (or arcs); these define a *graph*. If an ordering or direction is specified for each connecting line, the graph becomes a directed graph or *digraph*. Weights and/or signs for the arcs may also be added. A graph or digraph may have two elements connected by more than one line (circuits or cycles, respectively) or one element connected by a loop to itself (Fig. 1).<sup>1</sup>

Signed digraphs may have two kinds of cycles: 1) those having an odd number of – signs and known as negative, inhibiting, or deviation-counteracting and 2) those having an even number (or zero) – signs and known as positive, augmenting, or deviation-amplifying. A complex system characteristically has many such cycles, reflecting strong mutual, as contrasted to unidirectional, causality [3, pp. 140–142]. A preponderance of positive cycles is a clue to system instability.

Graphs include as a subclass hierarchy diagrams or *trees*. Trees are graphs with a single point as a source and branching as one moves away from the source. In a tree there is one and only one path between two elements; no circuits or loops are permitted.<sup>2</sup>

An impressive mathematical theory for directed graphs and related structural modeling concepts has been developed by Harary et al. [4] and Roberts [5]. Warfield [6] and his associates at Battelle Memorial Institute have worked diligently to advance the theory and application of unweighted digraphs—work usually subsumed under the heading Interpretive Structural Modeling (ISM).

Structural modeling (SM) always begins with a set of elements, the building blocks of the system. Where do they come from? The answer is that usually the choice is largely intuitive. The elements—variables, subsystems, goals, etc.—are chosen on the basis of individual or group experience, discussion, and literature search. It is highly unlikely that any systematic process can be found which insures a priori capture of all important elements. However, various procedures, which we refer to as “generating tools,” can be used to assist in drawing forth the elements (see [7] and [8], for a survey).

### Constraints

The most significant assumptions which underlie structural modeling are noted below.

#### PAIRWISE RELATIONSHIPS

The following example [9] illuminates the seriousness of this assumption.

Consider three elements A, B, and C. There are 6 pairwise relationships (e.g., A on B). However, the total number of possible relationships is 49 (e.g., A on A, AB on ABC,

<sup>1</sup>The definitions of cycles and loops are not firmly entrenched in the literature. Some authors use the word “loop” to include cycles in digraphs.

<sup>2</sup>A relevance tree is a tree with weight numbers attached to the nodes and relevance numbers associated with the connections. It is a well-known concept in technological forecasting.

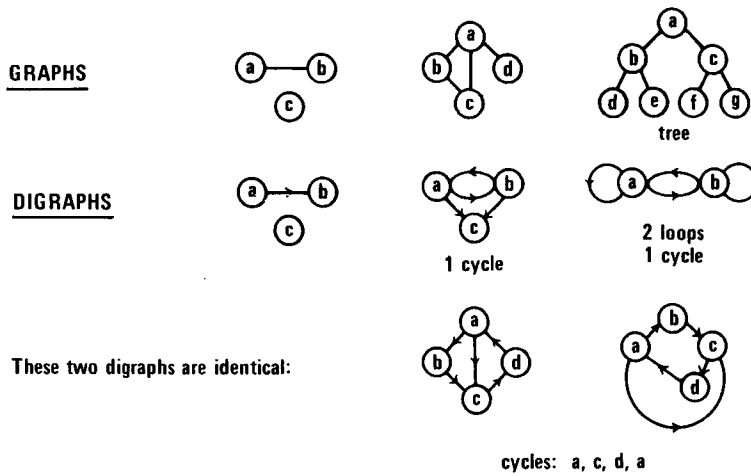


Fig. 1. Basic connections.

C on BC). With 10 elements the number rises to over 1 million. In fact, the formula is  $(2^n - 1)^2$ , where  $n$  is the number of elements. Clearly, the vast majority of relationships or cross impacts is non-pairwise, i.e., two or more variables act together and inseparably to impact another variable. Most SM techniques ignore such possibilities.

TRANSITIVITY (if  $A \rightarrow B$  and  $B \rightarrow C$ , then  $A \rightarrow C$ )

The appropriateness of this assumption, which is inherent in most techniques, is almost always taken for granted.

LINEARITY

This means that the principle of superposition holds, i.e., that the result of applying input  $A + B$  can be inferred from the results of applying input  $A$  and input  $B$  to the model separately. As a consequence complex synergisms are ignored. If the model is linear, it is sufficient to specify the interactions in terms of pairwise ones. However, if all the interactions are pairwise, it does not mean that the model is linear. Cearlock [10] distinguishes between linearity of systems and linearity of equations. A system is linear if all the terms in the mathematical representation are functions of only one state variable. Thus, if  $x_i$  are state variables,

$$x_3 = ax_1^2 + bx_2^2 \quad (a, b \text{ constant}) \quad \text{denotes a linear system}$$

$$x_3 = ax_1x_2 + bx_1 \quad (a, b \text{ constant}) \quad \text{denotes a nonlinear system.}$$

The equivalence of graphs and matrices holds only for linear systems.

A necessary but not sufficient condition for a set of equations to be linear is that the interaction coefficients be constant (i.e., state independent). A linear system may have nonlinear interaction coefficients.

STATIC AND DYNAMIC BEHAVIOR

Existing structural models fall into the following four categories with reference to time behavior.

*Static models.* The system is invariant over time. The work of Harary et al. [4] and Warfield [6, 11] makes this assumption.

*Transient or pulse process models.* A pulse applied to a variable (node) is propagated in accordance with some rule, e.g., instantaneously to nodes directly connected, and in the subsequent time interval to nodes one link removed. Once the pulse has been propagated there is no further change unless a new pulse is triggered. The pulse is a delta function which moves one connection along a path in a unit of time. (Some SM techniques can accommodate specified propagation delays.)

*Uncalibrated dynamic models.* The rate of change of a variable (i.e., its derivative) over a time increment is specified. Time histories are computed for all variables. However, these trajectories must be interpreted qualitatively. For example, in Kane [1] the variable "auto usage" is plotted versus time upon execution of the model. But the time scale is uncalibrated. We can conclude that auto usage increases, but not that it increases, say, 10% in 5 years. This constraint in certain models is the result of the algorithm, not the uncertainty in the input. Misinterpretation of such qualitative output in quantitative terms is a frequent occurrence.

*Calibrated dynamic models.* The conventional time trajectories developed in systems simulation are calibrated, i.e., the variable is plotted against a meaningful time scale. This is the case in system dynamics models, for example. There are structural models that also have this capability.

One of the most serious—and valid—criticisms of dynamic models is that they consider the variables as functions of time, but assume that the model structure is invariant.<sup>3</sup> The ability to develop new structures is the hallmark of the successful evolution of living systems. Yet hardly any of the SM activities concern themselves with the process of structural change.

#### CUMULATIVE VERSUS PROPORTIONAL CONNECTIONS

The connections between system elements may be cumulative or proportional, as pointed out by Burns and Marcy [14] and by Dudek et al. [15]. This difference is elaborated in Table 1.

The connection between the two variables may involve both cumulative and proportional relations:

$$\dot{X} = A X + B \dot{X}$$

Each tool must be examined to determine the connections allowed by its algorithms.

<sup>3</sup>The world dynamics models of Forrester [12] and Meadows et al. [13] exhibit this characteristic. Critics have noted that it is completely unrealistic that an economic or political system will operate in a structurally fixed manner while crises of unprecedented proportions appear imminent.

**TABLE 1**  
**Two Types of Connection**

Cumulative Connection	Proportional Connection
Assume $x_i$ to be the impacted variable and $x_j$ the impacting variable, $t$ the time, $\alpha_{ij}$ and $\beta_{ij}$ constants.	
$\frac{dx_i}{dt} = \alpha_{ij}x_j(t).$	$\frac{dx_i}{dt} = \beta_{ij} \frac{dx_j}{dt}$
If $x_j$ is constant, we have	If $\frac{dx_j}{dt}$ is constant, we have
$x_i(t) = \alpha_{ij}x_j \cdot (t - t_0) + x_i(t_0)$ (1)	$x_i = \beta_{ij}x_j + \gamma$ (2) where $\gamma$ is also constant.
Matrix notation: $\dot{X} = A X$	Matrix notation: $X = B X$ (or $\dot{X} = B \dot{X}$ )
Note in eq. (1) that, with $x_j$ constant, $x_i$ continues to increase over time.	Note in eq. (2) that, with $x_j$ constant, $x_i$ is also constant.

Some authors identify the two types of connections in other ways:

<u>Cumulative</u>	<u>Proportional</u>	<u>Reference</u>
Long term	Short term	[1, 16]
Flow path	Information path	System dynamics; [14]
Dynamic input-output	Static input-output	[10]
Differential	Algebraic	[10]

### The Tools Studied

In identifying SM techniques we began with a set of about 35, added 30 by manual literature search and 35 more by a computerized search. Of these 100 tools, 20 were set aside as generating tools, 46 eliminated for various other reasons (e.g., lack of generality, lack of documentation), leaving 34 for further study. We then applied the following practical criteria:

1. The application of the method must be possible in a matter of days and for only a few thousand dollars.
2. The method must be easily understood and used by persons skilled in mathematics and modeling. Other persons or groups must be able to easily understand and use the method under the guidance of skilled facilitators and technicians.
3. The method must be very general in its range of applicability. For example, a computer algorithm used strictly to manipulate graph structures so that they will be easier to store within a computer is too specific.
4. The method must be fully implemented and tested in at least one case relevant to technology assessment (TA). A proposed conceptual model is difficult to evaluate.
5. The method must permit use of subjective data.

It should be stressed that *structural modeling is not inexorably linked to computers; much effective analysis can be done using pencil and paper.*

Seven specific methods involving digraphs and/or matrices were selected for detailed evaluation. In origin they are Canadian, English, French, and American:

ISM	[6, 11]
ELECTRE	[17, 18]
SPIN	[19, 20]
IMPACT	[21]
KSIM	[1, 16]
XIMP	[22]
QSIM	[23-25]

Brief descriptions of these techniques are presented below.

#### ISM

Interpretive Structural Modeling (ISM) is a computerized algorithm for arranging a set of elements in an ordered sequence or hierarchy in accordance with a given ordering relationship. By assuming the connections are transitive and pairwise, the computer obviates the need to compare all possible pairs. It requests the minimum number of comparisons, uses the algorithm to calculate the remainder and quickly determines the overall ranking of the elements. While the procedure seems unnecessary if the number of elements is small, it is very useful for a large set.

John Warfield, the foremost proponent of ISM, emphasizes the importance of abstracting empirical observations into a content-free model which can be easily manipulated. The results must then be interpreted in terms of empirical information; hence, the name Interpretive Structural Modeling.

Questions which have been raised concerning ISM include the "first element syndrome," (i.e., does the first element examined bias later comparisons?) and the voter paradox (i.e., individual transitivity, but group intransitivity). Neither appears to present serious constraints.

While the ISM program can discover that a number of elements may all be reached from one another, and thus coalesced into a cycle, the procedure may be modified to yield additional information concerning the connections among the elements in the cycle. In this "cycle resolution" process the participants provide more input by completing a weighted matrix of the elements identified in the cycle. Specifically, information about the intensity of each connection in the cycle is obtained and the computer uses a threshold concept to determine a suitable binary matrix in a series of steps.

#### ELECTRE

ELECTRE is a computerized algorithm for ranking a set of alternatives, when each has been rated on several criteria, or by several evaluators. The ELECTRE algorithm avoids some of the problems inherent in conventional multiplicative evaluation techniques. Comparisons among the alternatives (one pair at a time) are made for each criterion, and an index is calculated. The index is tested against three thresholds (which are set by the user) and the relationship between each pair of alternatives is determined as "strongly preferred to," "weakly preferred to," or "no preference." A ranking is developed from the preference matrix.

**SPIN**

Building on work in France and on the work of Roberts and others, McLean et al. developed a computerized structuring tool called SPIN. In addition to allowing users to perform pulse analysis, matrix powering, and feedback loop analysis of digraphs, SPIN also allows users to perform clique analysis, ordering, and simplex analysis.<sup>4</sup> These are useful for identifying subsystems and discovering patterns of relationship within a weighted digraph. McLean has made an important contribution by organizing various methods into a common framework. This permits structural analysis to become part of the structure development process. For McLean, the role of structuring tools is to help "get the problem right" [26], by allowing multiple models to be considered during problem formulation, i.e., by helping to integrate generating and structuring.

**IMPACT**

IMPACT is a structuring tool which computes the time behavior of a weighted digraph model. IMPACT uses an autonomous, continuous pulse process (see Roberts [5]), with bounded variables. Thus, it appears to operate much like KSIM, although the underlying mathematical models are quite different. Users develop a weighted digraph which is entered into the computer to estimate behavior and test alternatives. The IMPACT guidebook contains a description of the modeling process, and a listing of the short (250 statement) FORTRAN program. It has been designed as a classroom tutorial.

**KSIM**

KSIM focuses on the dynamic properties of a structure. KSIM begins by asking an expert group, or individual, to develop an interaction matrix (weighted digraph) and determine the initial values of the elements. This data is entered into a computer program which projects the values of the elements over time, taking into account all of the interconnections. The underlying model assumes that: 1) the system variables (elements) are bounded, 2) variables increase or decrease depending on the net impact of all the other variables, 3) a variable's response to impacts lessens as the variable approaches its bounds, 4) a variable's influence is proportional to its value, and 5) complex interactions are described by a looped network of pairwise interactions. A recursive formula based on these assumptions is applied to the initial values of the variables. The variables follow a basically S-shaped trajectory toward either the upper or lower limit.

**XIMP**

Moll and Woodside [22] have developed a computerized structuring tool called XIMP, which is based on a slightly modified version of KSIM. XIMP features a user-interactive computer implementation that has built-in structural analysis capabilities. The principal modification from KSIM is the incorporation of "base" values. The impact of an element at a point in time is proportional to the difference between its value at that time and its base value. If the element has a value less than its base value, then the sign of its impact is reversed.

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<sup>4</sup>A clique of a digraph is a subgraph for which all elements are connected; it can be considered as a subsystem. Ordering refers to the use of elementary row and column operations to reorder the adjacency matrix to achieve a nearly block-diagonal form. Simplex analysis is a way of grouping elements with a common property, e.g., elements that have similar connections to other elements.

The structural analysis in XIMP includes stability analysis, sensitivity analysis, parameter identification, and tracking optimization. The stability analysis is closely related to that of Roberts. Criteria are developed by linearizing the XIMP equations near a stationary point and investigating the eigenvalues. Stationary points occur when each element has reached its limit.

#### QSIM

QSIM, which is similar to KSIM, but somewhat more elaborate, was developed independently by Wakeland. In QSIM, variables are not automatically bounded, the coefficients need not be constant, and the equations need not be linear. Users are first asked to develop an unsigned, unweighted adjacency matrix for the elements. Then, each binary connection is elaborated in terms of a graph called an interaction plot. An interaction plot portrays the rate of change of one element as a function of another element. Each interaction plot is treated as one term in a set of first-order differential equations which are numerically integrated. In order to model complex interconnections between more than two elements, QSIM allows for the use of "auxiliary variables" which are functions of the other elements of the model. The functions can either be polynomials or piecewise-linear, tabulated functions. The computer program is documented in a user's guide [25]. This guide contains a "walk through" of the modeling process.

It should be noted that SM is often a group activity. As such, it involves three distinct roles: the method technician, the facilitator, and the participants. These roles are discussed by Lendaris [8] elsewhere in this issue.

#### **A Structural Model of Structural Modeling**

It is useful to place the various pieces which comprise this SM fabric into context to understand their differing assumptions, input, and output. For this purpose, a model is presented wherein the "elements" are states of knowledge, either intermediate or final (output), and the "connections" are steps which lead us from one state to another. Three kinds of activity may occur in a step: 1) make an additional assumption, 2) add further information, and/or 3) execute an algorithm or operation.

The model, or "map," is shown in Figure 2. Encircled Roman numerals (and letters) identify types of output that can be obtained by using the various algorithms.

#### **Structural Modeling and Technology Assessment**

We recognize that a TA generally involves a number of component activities:

- Choose the initial team
- Gather information (listening)
- Analyze information
- Bound various open-ended sets
- Build the team
- Perform analysis—history, current situation, obvious future forecasts
- Project future environments
- Analyze impact of alternate technologies



Fig. 2. Structural model of SM tools.

- Identify fits, misfits, undecidabilities, and gaps<sup>5</sup>
- Determine affected individuals and organizations and their values
- Develop policy recommendations and analyze their consequences
- Communicate results

Armstrong and Harman [27] define four task areas in the TA process, as shown in Figure 3.

Critical evaluation of previously completed TAs indicates that explicit step-by-step methodologies have had a meager payoff. A striking common feature of the more effective TAs is an effort to fit methodology to the problem rather than to fit the given problem to an a priori methodology. These studies are characterized by a deep embedding or "immersion" of the team in the problem.

This suggests at once that the development of a single structural model for the TA process might prove counterproductive, tying the TA team to a Procrustean bed. Furthermore, TA is an evolving art and may use different inquiring systems in the coming years (e.g., dialectic process, application of the Allison models<sup>6</sup>).

These considerations suggest that the role of SM in TA be more like those sketched in Figures 4 and 5.

It follows that prescriptions for the use of SM in TA, e.g., "use KSIM in Step 3 of the TA" must be avoided. In the following section, we provide several samples, cautioning the reader that the same modeling technique may not be useful in every analogous context.

### Some Examples

The three following illustrations present a sampling of SM applications to TA.

#### THE MINI-TA

First-cut impact assessments can be rapidly conducted by developing and inspecting signed digraphs. In the Rehabilitation Technology TA [15], a two-day workshop of experts generated paper and pencil causal diagram (signed digraph) models of the consequences of various rehabilitation technologies. The system behavior implied by these causal structures was generated by a KSIM-like computer program called GSIM and fed back to the experts *before the workshop was over*. Then the experts changed the causal diagram structure in order to "produce behaviors which were more consistent with the collective understanding of the behavior" [15, p. 1-7]. According to the modelers, this speedy two-day workshop procedure "enhanced the participants' capability: 1) to generate consequences and, 2) to understand the important issues which interact to produce the behaviors of interest." The workshop participants' reaction to the use of manual causal diagramming was that it "helped provide some structure and aided assessment." Some participants judged that causal diagramming was "highly valuable and made analysis much easier and aided understanding," while others were either undecided or thought causal diagramming accomplished little or nothing.

<sup>5</sup> Undecidability does not mean uncertainty, but refers to questions which can only be dealt with by a metaconcept (e.g., centralization vs. decentralization). Gaps refer to lack of interaction between elements or to missing elements.

<sup>6</sup> Cf. Linstone et. al. [7], Linstone et al. [28].

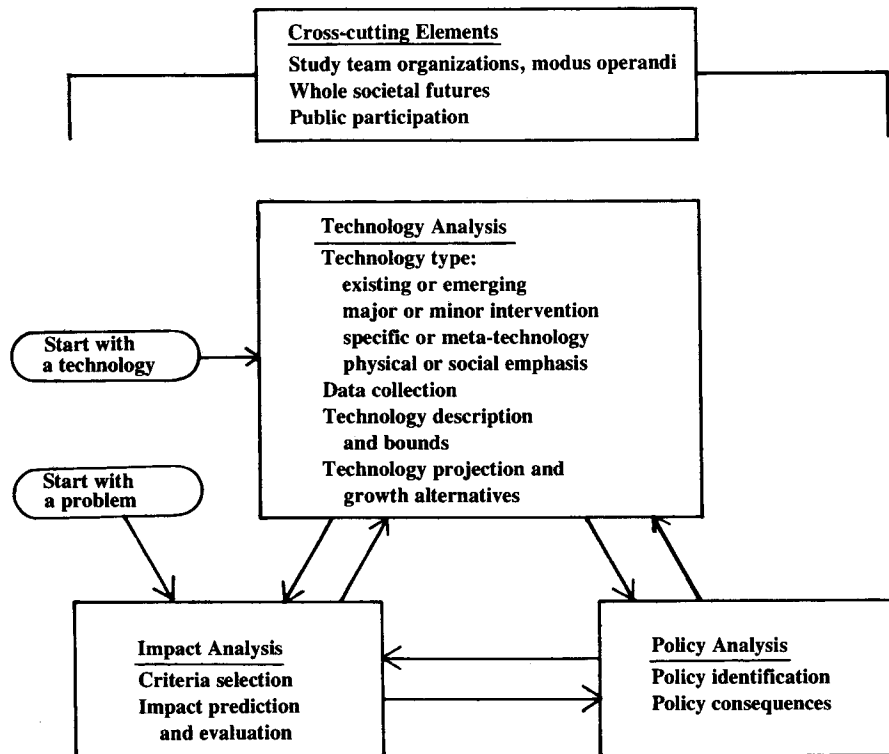


Fig. 3. Tasks in the TA process.

The 25 workshop participants reacted similarly to feedback of the computer simulation. Twelve judged that this step was either helpful or highly valuable. Four judged the step to be of little or no help, eight were undecided, and one participant concluded that this step hindered more than it helped.

After the two-day workshop, in-house modelers refined and generalized the causal diagrams, using after-session inputs from the session participants, finally merging subsystem digraphs into a "generic" structural model which influenced the development of a system dynamics model [15, p. 1-7].

Why did this TA modeling team use causal diagramming and GSIM simulations? One of the main reasons was that GSIM had been developed in-house, so skilled facilitators and technicians were readily available.

Another set of reasons has to do with matching the properties of the SM tool with their particular problem, which was to gather up missing data about consequences of rehabilitation technology intervention. They considered using Warfield's ISM and compared it to GSIM by running an in-house ISM session. They found ISM sessions to be

... somewhat less useful for our purposes because they

- (1) tended to emphasize the hierarchical aspects of the systems to the detriment of the feedback aspects,
- (2) were too time-consuming to be practically accomplished within the time frame allocated,
- (3) did not provide any indication as to behavior of the dynamic systems being worked on [15, p. 1-9].

In the next example the experience with ISM was quite different.

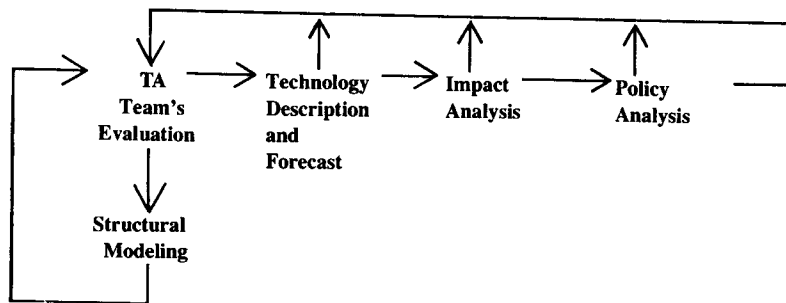


Fig. 4. One view of the role of SM in TA.

**IMPACT ANALYSIS: DEVELOPMENT OF A HIERARCHY OF MANY LEVELS AND CLARIFICATION OF INDIRECT IMPACTS**

Consider the impacts on society of a transition to hydrogen-fueled automobiles. We recognize that privately owned automobiles and publicly owned fleet automobiles are but one part of a complex system which we call "the automotive transportation system," and it is this complex system which was of concern in the Hydrogen Economy TA [29].

At a gross level of abstraction, the complete system is assumed to be made up of six elements:

1. vehicles
  - private personal
  - private fleet
  - public fleet
2. the fuel producer-distributor-retailer network,
3. the vehicle manufacturer-sales outlet network,
4. the vehicle maintenance-repair facility network,
5. the roadway network,
6. the many stakeholder groups in society that are implied by 1 through 5 above.

Thirty societal groups, institutions, and stakeholders are then identified as being represented by the first five physical system elements above:

1. oil companies
2. utility companies
3. the capital market
4. automobile manufacturers
5. auto parts manufacturers
6. auto consumers
7. cryogenic industry
8. insurance companies
9. insurance consumers
10. pipeline companies
11. natural gas producers
12. government regulatory bodies
14. distribution hardware producers

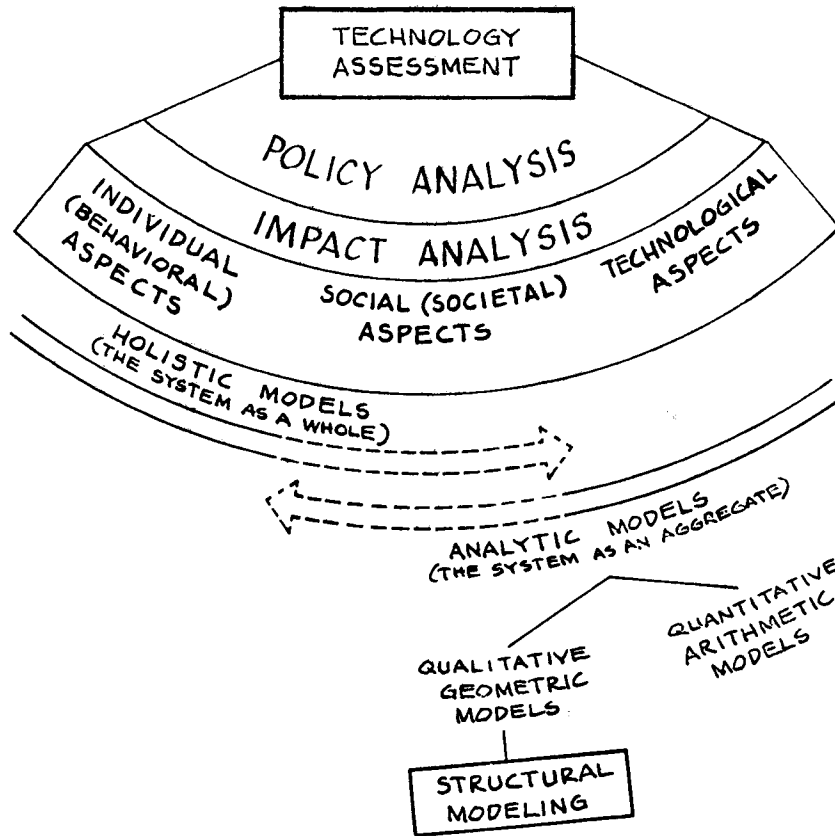


Fig. 5. Another view of the role of SM in TA.

- 15. fuel dealers and employees
- 16. unions
- 17. fuel consumers
- 18. mechanics
- 19. factory workers
- 20. vehicle passengers
- 21. emergency/accident crews
- 22. accident bystanders
- 23. vehicle owners
- 24. vehicle drivers
- 25. urban residents
- 26. air quality government regulatory bodies
- 27. individuals in general
- 28. U.S. citizens
- 29. society
- 30. nearby residents to distribution centers.

The relations we wish to model are:

1. Impacts on the work force
  - job security
  - training
2. Economic impacts
  - retraining
  - capital investment
  - price changes
  - job security
3. Institutional impacts
  - ownership
  - liability
  - regulation
4. Impacts on individual values
  - personal safety
  - independence/self-reliance
  - health
  - aesthetics
  - personal freedom
  - national security

We are not interested in measuring these impacts in quantitative terms of money, power and/or number of people involved—we merely want to know what affects what. The time boundaries of the model are taken to be 1975–2020, since in our judgment most of the “action” in the hydrogen economy will not occur until about 2000. Since the impacts are so far in the future, we are willing to weight impacts only as “major,” “moderate,” or “minor.”

ISM is used to order the 35 elements into a hierarchy, yielding the graphical representation shown in Figure 6. This ISM output may be compared to a table of impacts involving the same elements in the Hydrogen Economy TA. The ISM graphical structure shows chains of impacts, whereas the Hydrogen Economy TA impact table format shows only direct impacts.

By tracing these impact chains, the reader discovers errors of omission and commission. For example, the element *capital market* (10) in Figure 6 appears to have no exiting arrows, i.e., no impacts on other model elements. The ISM process encourages the probing of neglected impacts and the revision of system perceptions.

#### POLICY ANALYSIS: EFFECTS OF POLICY CHANGES AND SENSITIVITY ANALYSIS

The use of SM to suggest policy changes and probe their impacts is well established. Kane [1], in his basic KSIM primer, illustrates the method by an urban automobile traffic growth example and asks: What simple policy or mix of policies can reverse the growth trend? The KSIM results echo Garrett Hardin's policy dictum, “you can never merely do one thing.” Roberts [5, pp. 189–191] develops a signed digraph of electrical energy demand and is led thereby to the policy concept of “rate structure inversion.”

Two examples are considered here. In the first, the United Kingdom Private Car Model [30], the aim is to understand how the transportation system works as well as the effect of policy changes on the major descriptive variables. The SPIN model is used for

1. structuring a "first guess" interaction matrix and analysis of it,
2. review by experts and alterations in the structure,
3. several iterations of this process until a plausible model is obtained.

There are 26 variables, some quantitative, others qualitative. The system consists of two linked subsystems, "short haul" and "long haul." There are 62 interactions and 14 cycles. Of the 26 variables, 11 are sources and sinks, so that all cycles involve only 15 of the variables (and 31 interactions). These are:

#### Variables for U.K. Car Cycles

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CAR US L	car use for long distance travel
DELAYS L	average delays in long distance travel
ROADS L	quality and capacity of long distance roads
AOATM L	availability of alternative transport mode (long distance)
CAR US S	car use for short distance travel
DELAYS S	average delays in short distance travel
ROADS S	quality and capacity of roads in urban areas
AOATM S	availability of alternative short distance transport mode
POLLUT	pollution
CAP COST	capital cost of car
PDRL	perceived demand for roads (long distance)
LDRS	perceived demand for roads (short distance)
UOATM L	use of alternative transport mode (long distance)
UOATM S	use of alternative transport mode (short distance)
CAR OWN	car ownership

Figure 7 shows the feedback cycles of the structure. Items such as fuel price, fuel use, and fuel economy are included in the model, but are not involved in any feedback loops.

A sensitivity analysis is performed here by pulsing sources and monitoring sinks. The plotted output of SPIN is not interpreted as a conventional time trajectory, but as a qualitative statement about the transient feedback in response to a particular pulse. For example, variables may increase or decrease monotonically (positive feedback dominating), stabilize (negative feedback), or go into exploding oscillations in response to some particular pulse.

The second example involves a model developed by Gerardin [31] to search for "policy levers" in the French National Plan. Gerardin studied the conflict system between managers and labor unions in this industrialized society. Our use of SPIN revealed that Gerardin's 12-variable model had 257 feedback loops. The five strongest loops were determined and it was found that they contained five variables. Both SPIN and QSIM were then applied to the less complex five-variable model. The output helped to determine which variables would be the best future indicators of change (and therefore the most cost-effective to monitor) and which "policy levers" might be most cost-effective for each side in the conflict.

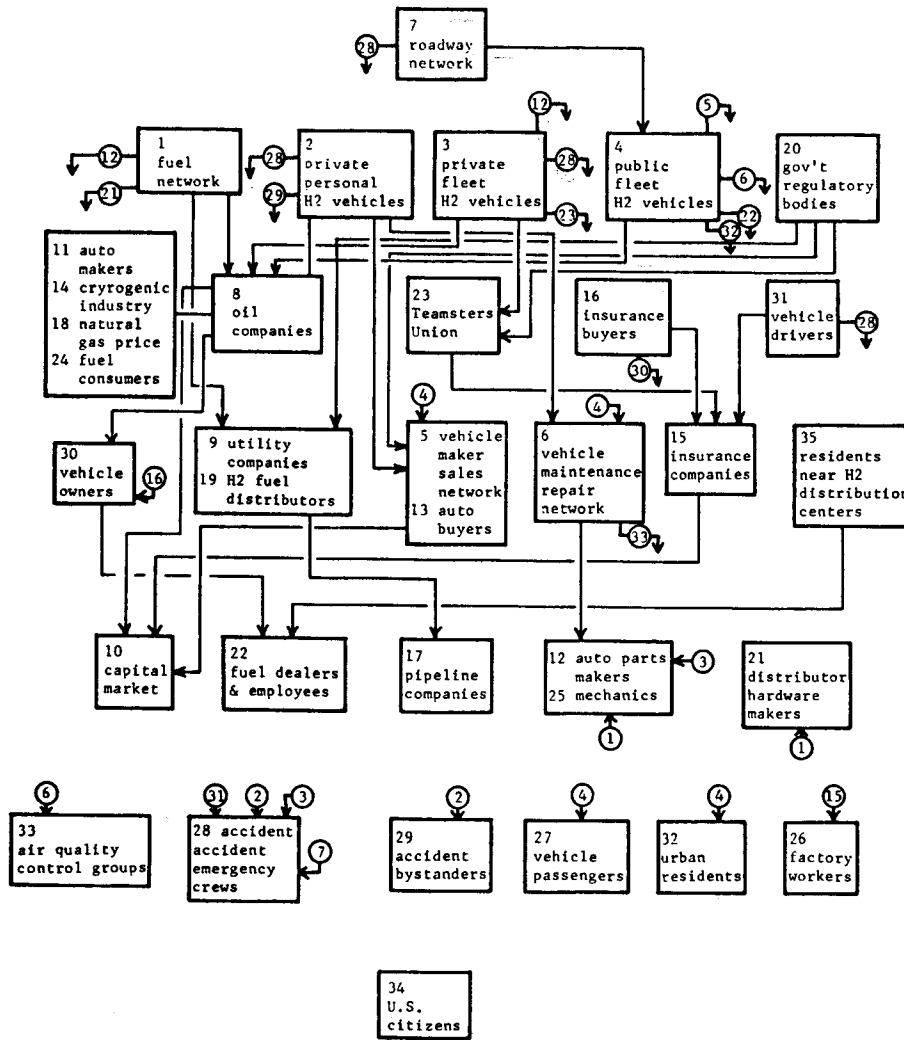


Fig. 6. Impacts of hydrogen-fueled autos.

We found SPIN a particularly attractive tool, flexible and “fun” to use. It fostered ideas and proved very effective in gaining an understanding of the model structure.<sup>7</sup>

#### Evaluation and Comparison of SM Tools

All of the SM tools we studied could be applied in a few days, are relatively inexpensive, but require specialists if proper use is to be assured. Some tools are very

<sup>7</sup> We also applied SPIN to a model suggested by the 1977 Carter Energy Plan. There are 46 variables, 67 connections, and 9 feedback cycles (only 3 of which contain more than 2 variables). This suggests that some planners may have a curiously hierarchical view of the energy system. The most striking feature of the complex digraph was the identification of the variable “federal deficit” as an awesome sink dominating the flow pattern [7, vol. 1, pp. 93-98].

versatile, because the elements and connections can have almost any conceivable meaning; others are limited, because the elements and connections have specific meanings.

The set of criteria used for comparison of the various tools is subdivided into five categories: general, connection-related, vital algorithm properties, group aspects, and computer implementation. They include the following items discussed below.

GENERAL CRITERIA

The number of elements that can be effectively handled varies considerably. Assigning the upper limit (or lower limit) is highly subjective. We offer our estimates as guidelines for persons new to SM; the experienced modeler will develop his or her own limits relative to specific tools. Most methods require a computer; however, one SM method can be run on a programmable calculator, and several achieve useful results by manually tracing out implications.

CONNECTION-RELATED

The two basic types of connections—cumulative and proportional—were defined earlier. There are, of course, more complex relationships and some methods permit the following.

*Functionally dependent connection.* Relation between two variables is nonconstant and dependent on other factors. Example: interest rate (impacting) is 5% for first 5 years and 6% thereafter (savings is impacted variable).

*Delayed connection.* The impact may take effect only after a time delay. Example: snowfall (impacting) to runoff (impacted). Only one of the methods permits specifying time delays.

*Non-pairwise connection.* Previously discussed. Example: relations among members of nuclear family.

VITAL ALGORITHM PROPERTIES

*Essential assumptions.* Many methods require that linearity be assumed. One requires that transitivity be assumed. Only some methods can incorporate empirical data when it is available (however, see Gur [32]).

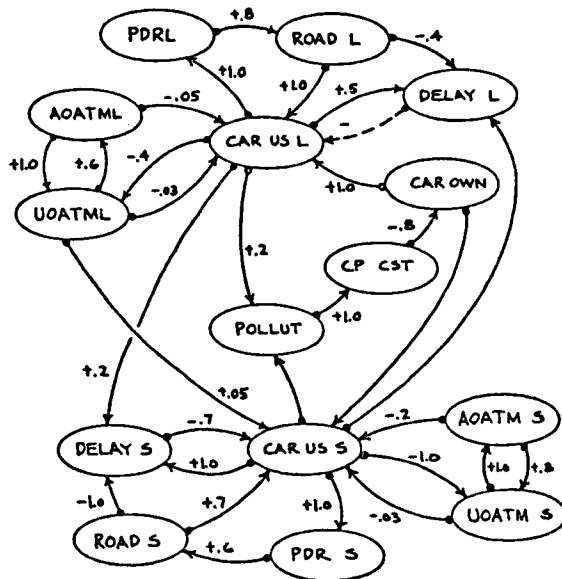


Fig. 7. Cycle structure of UKCAR.

Other options include:

*Qualitative emphasis.* Focus is on subjective, inexact input producing meaningful output (but not precise, quantitative forecasts of behavior).

*Causal loop emphasis.* Focus is on tracing causal paths and discovery of the presence or lack of feedback cycles in the model. This may occur either in the building of the model or in the analysis stage.

*Time behavior limitations (see Fig. 8).* Consisting of:

*static*—constant over time

*transient*—short-term response to changes

*dynamic uncalibrated*—algorithm computes behavior over successive time increments, but an increment has no precisely defined duration, and the interpretation of time is left to the user

*dynamic calibrated*—algorithm computes behavior over successive time increments, and an increment has a specific temporal definition.

#### GROUP ASPECTS

*Allowance for disagreement.* Explicit allowance for disagreement and multiple criteria is made in one of the SM methods studied.

*Ease of use and communicability.* A summary measure of the number of judgments needed for tool use, the mathematical complexity, type of data required, form of output, and sophistication of human-machine interface.

The ease of communicating the model and results to nonmodelers varies substantially, i.e., some tools are easier to use by lay groups than others.

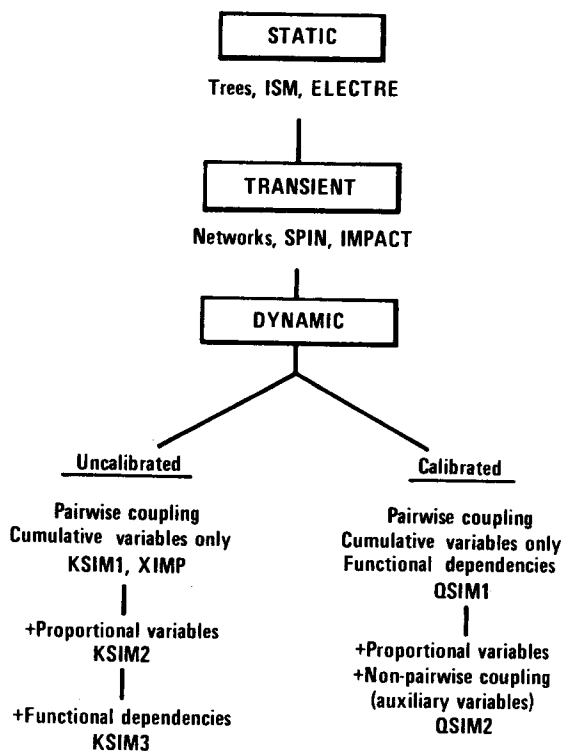


Fig. 8. Static and dynamic behavior.

*Explicit group process in making subjective judgments.* A measure of the explicitness of the formulation and communicability of the procedure which makes use of the group. Only two tools feature an explicitly designed group process for making subjective judgments.

Figure 9 and Table 2 summarize the characteristics of the tools, as discussed up to this point.

#### COMPUTER IMPLEMENTATION

The seven methods that use a computer program were also compared with respect to their human-machine interface. The criteria:

- anticipates user errors—catches errors without losing data and/or provides useful defaults
- provides complete editing diagnostics—tells exactly what went wrong if an error occurs, so that it can be easily fixed
- provides display upon user demand—user controls what is printed at the terminal
- same purpose can be achieved by multiple commands
- operator inputs echoed—traces of inputs readily available (other than original)
- easy to learn and use
- provides a tutor for self-teaching—either a “long prompt” level or a special procedure
- versatile—easy to add new commands; modular design, command processor orientation
- rapid response—minute turnaround times
- easy to expand model—add variables
- records inputs for succeeding runs—ability to stop part way through the procedure without losing data
- easy to save model—simple command

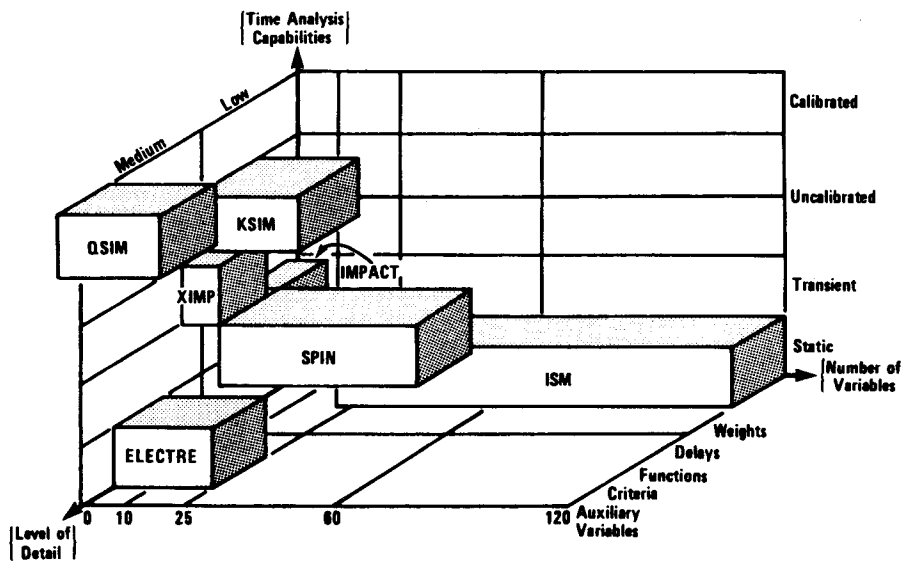


Fig. 9. Comparison of SM tool characteristics.

TABLE 2  
General Comparison of Tool Characteristics

	TREES	ISM	ELECTRE	NETWORK	IMPACT	SPIN	XIMP	KSIM3	QSIM2
Basic									
Maximum number of elements (approx.)	20*	120	25	10*	10	60	10	25	25
Computer required?	No	Yes	Yes	No	Programmable hand calculator	Yes	Yes	Yes	Yes
Connections									
Cumulative	NA	NA	NA	No	No	No	Yes	Yes	Yes
Proportional	NA	NA	NA	Yes	Yes	Yes	No	Yes	Yes
Functionally dependent	No	No	No	No	No	No	No	Yes	Yes
Non-pairwise	No	No	No	No	No	No	No	No	Yes
Delays	No	No	No	No	No	Yes	No	No	No
Vital Algorithm Properties									
Essential assumptions		Transitivity			Linear System	Linear System	Linear System	Linear System	
Qualitative emphasis	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Causal loop emphasis	No	No	No	Yes	Yes	Yes	No	No	No
Time behavior limitations	Static	Static	Static	Transient	Transient Bounded	Transient	Uncalibrated dynamic, bounded L	Uncalibrated dynamic bounded L	Calibrated dynamic



The comparisons are summarized in Table 3.

Procedures and criteria for evaluating *models* abound in the literature (e.g., [33, pp. 12–48].<sup>8</sup> While these are valuable, they do not address the problem of evaluating a *method* rather than a model. Of course, one could use the method to develop a reasonable sample of models and apply the criteria to the models. Then, if most of the models pass the criteria, the method is assumed to be valid also. One problem with this approach is that a well-designed tool in unskilled hands will not produce quality results, nor will such a tool perform when applied to the wrong task.

By specifying desirable values for the various tabulated characteristics in a TA context (Table 4a), we could classify the seven tools which use computer programs into three levels (Table 4b).

The combination of factors discussed in the previous section have, we hope, instilled caution in the reader as to the weight given such overall rankings.

### Structural Pluralism

Study of the SM tools at once suggests that multiple models using diverse tools might effectively overcome the limited perspective of any one model. In the words of McLean and Shepherd [30] on the UK car study.

What would emerge, we hoped, from this exercise would be an array of (around 20) alternative models representing the way in which various people *think* the UK transport system works. Now, some of these might be in contradiction—highlighting both the theoretical and ideological differences between experts and the extent to which apparent differences can be resolved. This approach to modeling has been called by the authors “structural pluralism”. . . . To sum up, the ultimate purpose of the structural modeling exercise [was] twofold:

- to highlight different assumptions made by various “experts” in government and research centers
- for a given set of assumptions, make *broad* projections about likely changes in important variables with respect to selected policy changes.

Since SM is relatively quick and inexpensive, it is quite practical to take a pluralistic structuring approach in situations where traditionally only a single model would be created.

The most obvious application of the “pluralistic structuring” concept in TA is in working with diverse groups—each of which develops its own model. But the same concept can also be implemented along the *time* dimension, as may be necessary in some TAs. For example, Ed Lawless, team leader of a TA on pesticides [34], told us that the team had learned that major structural changes in the laws regulating chemical pesticides had been coming closer and closer together in time (and each change was more comprehensive in scope and more radical).<sup>9</sup> Historically, the *major* structural changes occurred in 1910, 1947 (amended in 1959, 1961, and 1964), and 1972 (amended in 1975). If the time scope of the TA study is 20 years into the future, then multiple structural models

<sup>8</sup> Note that learning models involving ill-structured systems in a future setting pose validation problems very different from those of conventional models of scientific phenomena which are verifiable by experiments and hard data.

<sup>9</sup> A similar phenomenon was observed by Cetron and Clayton [3, p. 222].

TABLE 3  
Comparison of Human-Machine Interface Characteristics

	ISM	ELECTRE	SPIN	IMPACT	XIMP	KSIM	QSIM
1. Anticipates user errors	yes	no	yes	no	yes	no	yes
2. Provides complete editing diagnostics	<sup>a</sup>	no	yes	no	no	no	no
3. Provides display upon user demand	yes	yes	yes	no	yes	yes	yes
4. Multiple commands achieve same purpose	no	no	yes	no	no	no	yes
5. Operator inputs echoed	no	no	yes	yes	no	no	yes
6. Easy to learn and use	yes	yes	yes	yes	yes	yes	no
7. Provides a tutor for self-teaching	no	no	yes	no	no	no	no
8. Versatile—easy to add new commands	no	no	yes	no	no	no	no
9. Rapid response	yes	yes	yes	yes	yes	yes	yes
10. Easy to modify model	yes	yes	yes	yes	yes	yes	yes
11. Easy to expand model	yes	yes	yes	no	no	no	no
12. Records inputs for succeeding runs	yes	no	yes	no	no	no	no
13. Easy to save model	yes	yes	yes	no	yes	yes	yes

<sup>a</sup>Fitz version: yes

of government policy implemented in law would seem necessary—perhaps five of them (one every 3 to 5 years). This is feasible with the quick and inexpensive SM tools.

We illustrate the concept of pluralistic structuring by the application of SM to urban mass transportation planning.<sup>10</sup>

**TABLE 4a**  
**Characteristics Most Relevant in a TA Context**

Very Important	Important
Handle many elements	Non-pairwise connections
Qualitative emphasis	Delayed connections
Ease of use and communicability	Cumulative and proportional variables
	Explicit group process for subjective judgment
	Provide dynamic behavior

**TABLE 4b**  
**Classification of Tools**

Useful: ISM, KSIM, SPIN
Potentially useful: QSIM, IMPACT, ELECTRE
Problematic: XIMP

#### DEVELOPMENT OF SIGNED DIGRAPHS: PAPER AND PENCIL ANALYSIS

Initially, we generated a list of sixteen elements and ordered them with the aid of ISM. In the process the computer asked for 44 pairwise comparisons (out of a possible maximum of 120). Next, a citizen group and a group of professional planners were consulted. The citizen group used the blackboard to develop a signed digraph of the factors which, in its view, were most significant for mass transit usage (Fig. 10). Manual analysis of the digraph suggested that "convenience" was very important. The experts' model proved to be entirely different. They were concerned with certain policy decisions, e.g., increasing parking fees in the central business district to influence use of mass transit, transit revenue, and bus fares. Their model had twelve elements and, surprisingly, no loops (Fig. 11). The elements were more precise than those of the citizen group, but did not include the latter's *energy use* variable.

Comparison of the two unweighted signed digraphs underscores the thought of Kawamura and Christakis [35, p. 9]:

1. *Structural models may or may not reflect reality.*
2. *Structural models do reflect the perceptions of the model builders.*  
In this way they:
  - a. Identify elements considered important.

<sup>10</sup> For details, see Linstone et al. [7].

- b. Indicate the relation of the elements to one another.
- c. Indicate the logical implications of the relations, as seen by the model builders.

To put it less formally, in using structural modeling, you find out as much (or more) about the person(s) doing the modeling as you do about the system being modeled.

#### DEVELOPMENT OF CITIZEN MODEL USING COMPUTER

The citizen model was probed further by adding weights and delays for each connection. This proved to be a difficult task, requiring considerable direction from the facilitator. Then SPIN was used to perform an indirect path analysis to identify relative sources and sinks. Next, a SPIN circuit analysis was undertaken; it indicated that the strongest feedback loop is the *auto/hassle* loop and that most others have significant delays (Table 5).

Following this, a series of pulses was applied, one at a time, to each of the variables except *energy use*. When the pulse was applied to either *auto use* or *hassle*, wide fluctuations were produced (due to the large number of unbalanced feedback loops). When a pulse was applied to convenience of *mass transit use*, the reaction was much more subdued (due to the longer delays and relatively smaller weights.) Thus, improvements in mass transit convenience may not be amplified as suggested by the earlier paper and pencil analysis.

Finally, a dynamic analysis was done. The initial efforts involved cumulative connections only (XIMP and KSIM1). The difficulty experienced in obtaining reasonable

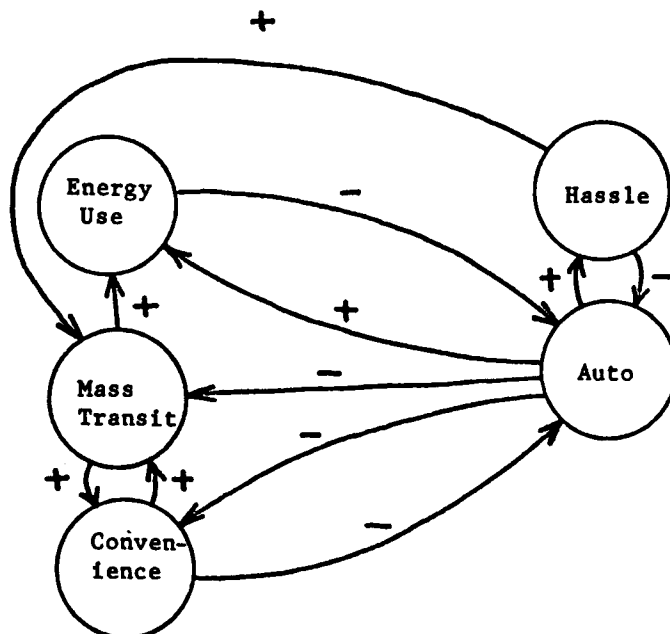


Fig. 10. Citizens' digraph.

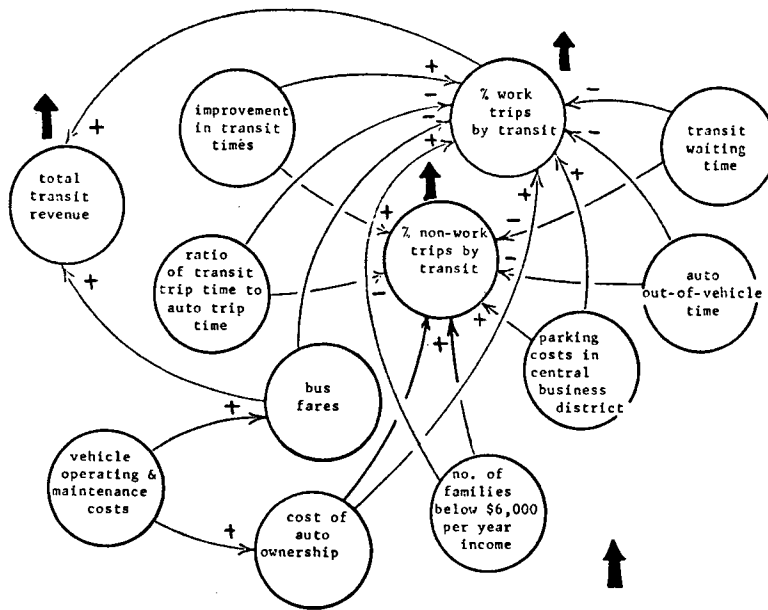


Fig. 11. Professional planners' digraph.

behavior led to the use of both cumulative and proportional connections (KSIM3).<sup>11</sup> The subtleties of distinction required much guidance by the facilitator. Relative scaling of the importance of the two types of connection (and multipliers) can be an irritant. Typical results are shown in Figure 12. For a better idea of the time span of events, i.e., a calibrated output, QSIM2 was used. The variables having proportional connections in the KSIM3 model became auxiliary variables in QSIM2. Specification of an equation and/or set of table functions for each auxiliary variable proved difficult and required strong direction from the facilitator. The variables having cumulative connections became *state* variables, and a set of interaction plots had to be specified, again with expert assistance. For example, the group was tempted to treat the ordinate as the value of the variable, rather than its rate of change. The payoff of the difficult task of specifying the QSIM model is that the output is reasonable and provides a useful time scale (Fig. 13).

The SPIN method provides additional useful information about the transient response of the system to perturbations; however, some care must be taken in specifying the weights and delays. A pulse process should not be construed as a forecast of time behavior, but rather as an indicator of the stability characteristics of the structure.

We tried using XIMP on the citizens' model, but were unable to produce plausible results.

KSIM3 requires some effort to distinguish between proportional and cumulative connections, but the effort is well spent. QSIM2 is even more difficult to use, but the payoff is a time-calibrated output and the ability to specify a wider range of couplings between variables. Both produce a reasonable time behavior pattern.

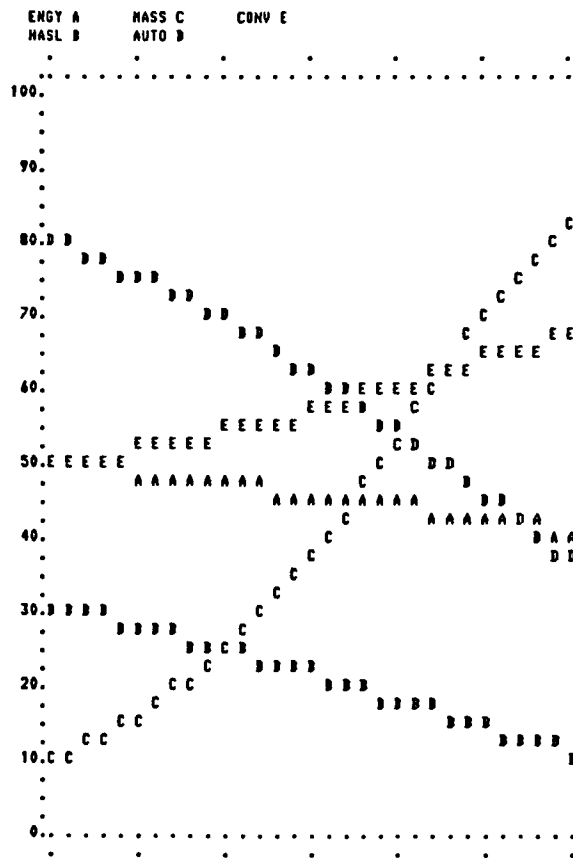
From this simple run-through, it should be evident that SM virtually forces considera-

<sup>11</sup>The connections into *mass transit use* and *auto use* were cumulative, the rest proportional.

**TABLE 5**  
**Critical Loop Analysis (Output of SPIN)**

Number	Start	Strength	Sign	Delay	Variables on the Feedback Loop		
1	ENERGY	-.20000E+00	-	12.0	AUTO		
2	ENERGY	-.12000E-01	-	12.0	AUTO	HASSLE	MASS T
3	ENERGY	0.30000E-01	+	12.0	AUTO	MASS T	
4	ENERGY	0.60000E-02	+	12.0	AUTO	CONVEN	MASS T
5	HASSLE	-.10000E-01	-	12.0	MASS T	CONVEN	AUTO
6	HASSLE	-.10000E+01	-	0.0	AUTO		
7	MASS T	0.25000E+00	+	12.0	CONVEN		
8	MASS T	0.25000E-01	+	12.0	CONVEN	AUTO	
9	AUTO	0.20000E-01	+	0.0	CONVEN		

Number of circuits found = 9  
 Number of circuits printed = 9



**Fig. 12. KSM run of citizens' model.**

tion of several versions of the problem under examination. The traditional modeler may be exasperated by this situation, but multiple perspectives are desirable, even necessary, if simple structural models are to be useful for learning purposes. The importance of a skilled facilitator is also evident.

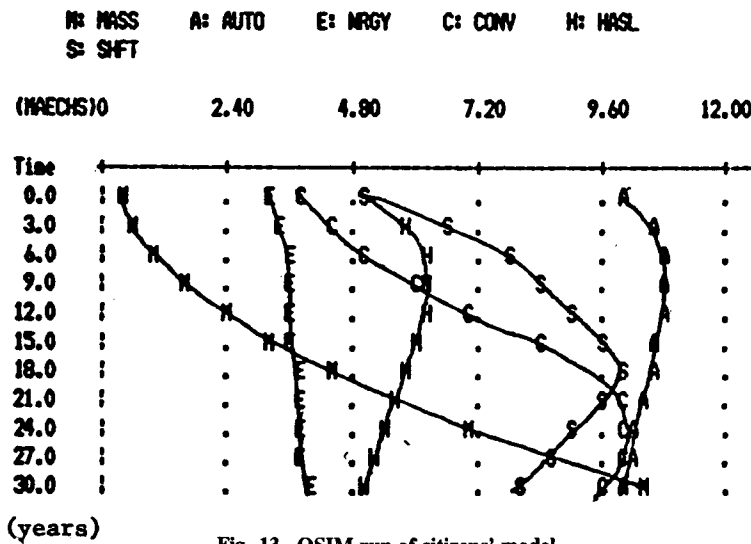


Fig. 13. QSIM run of citizens' model.

**DEVELOPMENT OF EXPERT MODEL**

This model (Fig. 11) was also subjected to a pulse analysis via SPIN. After some prodding by the facilitator, the planners added another variable and seven links, producing 12 feedback loops. The variable with the most impact on overall model behavior was identified using the SPIN indirect path analysis. At one point, the question of how to stimulate mass transit arose. What would be the best strategy? The alternatives were structured using ELECTRE II.

In sum, the SM session did not end until the planners felt they were no longer learning anything about their ability to conceptualize the system.

**Implications**

The proper use of SM in TA is not a trivial concern. The skilled analyst can use SM very effectively to lead the client through a complex chain of consequences resulting from the introduction of a technology; the unskilled analyst, with the same set of tools, utterly confuses the client. The able analyst might use SM to develop a meaningful roadmap for the TA; the mediocre one might unwittingly construct a map which misleads the user more than would the latter's own intuition. No amount of improvement in the tools can eliminate this concern. In fact, the relative simplicity of SM is a mixed blessing: easy use and easy misuse. As with statistics, it can be manipulated by the clever user to "prove" whatever he or she wants to demonstrate.

We have stressed:

- The advantage of interactiveness between human being and machine, i.e., between user and computer structural model.

- The subjective aspect of the modeling process, e.g., the difference in perception of the same system by two modelers.

The earlier discussion of SM brought out its inherent limitations. We particularly noted that:

- SM cannot assure the selection of the most significant elements and interactions.
- SM is not designed to yield meaningful output "numbers."
- SM is not holistic, but aggregative, i.e., it views a system in terms of its elements.

One inevitable consequence is a certain degree of personal fit between the user and the structural model, often making it difficult for one person to use another's model and replicate the results. A particular structure may open the door to understanding for some and strangle the imagination of others.

Another consequence is the inability to predict success if a team does structural modeling as a group effort. Two groups trying the same process may have very different results: one clicks, the other fumbles. Fortunately, the time and cost commitment is modest so that one can abandon the effort if it sputters.

Those who are by virtue of their background (in the hard sciences and engineering) reluctant to accept these characteristics of SM are advised to forego its use, rather than treat such tools as they would the comparatively rigorous models of the hard sciences. SM tools are, with few exceptions, analytic in nature. Figure 5 provides a constant reminder that they are inherently limited in their application. In Allison's terms [36], they belong to the "rational actor" perspective; they should not be expected to illuminate sufficiently the social or "organizational process" perspective and are likely to fail completely in the individual or "bureaucratic politics" perspective [7, pp. 133-134].<sup>12</sup>

We have pointed out that in most structural modeling methods, it is necessary to make the assumption that all relationships can be expressed in terms of pairs of elements. Most of the algorithms which develop subsystem identification, stability characteristics, and time trajectories depend on this assumption. Yet, we know that many aspects of complex systems cannot be reduced to pairwise relationships.

Concerning stability, we recall that the pulse stability analysis possible with SM provides a very restricted capability at best. Most of the available SM tools designed to permit a stability analysis impose the severe constraint of linearity (Fig. 2), yet very few systems of interest in TA are linear.

And the larger, or meta, aspects of system resilience can hardly be ignored. The behavior of complex living systems differs drastically from that of purely technological ones. C. S. Holling [37] has found that stability domains *change in size* as a result of management actions. In TA this would mean that policy decisions lead to feedback which alter the stability domains in ways not predicted by the SM tools available today.

It has been postulated that the most successful tools for modeling tend to be those which are problem-specific. It is, in fact, their success in that context which often leads to their generalization, inclusion in a "tool kit," subsequent misuse, and disrepute. The user must be cognizant of the dangers at all times and consciously suppress a rigid, uncritical attitude vis-a-vis his or her "favorite" tools.

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<sup>12</sup> Application of the Allison perspectives to TA is currently under study [28].

### Some Practical Recommendations

SM may be quite helpful in performing a TA, particularly in the first-cut portion of an iterative process, in a mini TA, in components of impact and policy analysis, and in communicating the results of a TA. Some considerations must be kept in mind, however:

1. *Do not use computers unless paper and pencil prove unmanageable.* Try to construct digraphs, trees and/or hierarchies manually first. You will be surprised how much can be learned from such an effort. Computers are needed for quasi-static systems if the number of elements is large and for dynamic systems which are known to involve complex interactions among the elements. But we have often found that the learning which occurs during, and as a result of, computer sessions is less than expected. This comment does not belie the value of structural modeling, rather it suggests that the computer be used, if needed, only after manual efforts at SM.
2. *Do-it-yourself structural modeling (with expert support) is nearly always preferable to buying packaged studies done by outside organizations.* Much, if not most, of the value of SM comes from the hands-on activity, the process rather than the output. This is where the learning is most effective and where the insights are gained.

This is the same point as that made by the great applied mathematician Richard Bellman about all mathematical modeling and simulation: "In many cases we learn most from the construction of the model" [3, p. 102].

3. *Do not take for granted the important built-in assumptions that accompany the use of an SM tool.* Neither human/societal nor ecological systems can always be approximated by linear models. Example: loop analysis applied to linearized versions of the Volterra predator-prey equations leads to serious errors in the determination of stability properties [10, p. 78].

Transitivity is necessary for ISM, but may not be acceptable. Example: in energy source development, natural gas affects oil and nuclear energy affects natural gas—but nuclear energy does not affect oil (too late in time; see Marchetti [38]).

Pairwise-only connections between elements are assumed in nearly all tools (notable exception: QSIM2). However, societal relations cannot always be described as pairwise. Examples: various vested interests in "lobbying," states in international relations. Considerable subtlety is needed in properly interpreting the time behavior representation of SM tools. Some are quasi-static, others have an uncalibrated time scale, the rest have limited dynamic range.

Use of multiple models and of other, non-SM approaches, such as historical analogies and precursor analyses, is usually desirable.

4. *Digraphs are at least as important as matrix representations* when direct connections are subjectively estimated. Faced with a matrix format, the user is prone to fill in most of the possible entries. But the connections are often indirect, a fact more easily recognized in a digraph.

The widespread use of matrices in the development of structural models has led to many modeling errors. Unless the number of variables and links is very

large, we recommend that digraphs be used in the early stages. They can always be converted to matrices for entry into computer programs if necessary.

We recommend that the person considering the use of SM first attempt to develop a digraph of at least a subset of the elements of concern. The behavior of the system may be inferred by inspecting feedback loops and the connections to each element. If this attempt fails, or if the implications of the digraph are difficult to interpret, then it may be useful to engage a consultant skilled in SM.

If the initial experience proves fruitful, then it is possible to determine whether SM consultants should be drawn in to help build structural models with a large number of elements (e.g., SPIN or ISM). Once consultants have produced worthwhile results and more analyses of this kind are anticipated, the possibility of implementing one or more SM tools in-house should be considered. This includes access to the available computer programs and learning (by doing) how to use the method.

5. *ISM as a precursor to KSIM, SPIN, or any method using a causal digraph as input is likely to lead to errors.* ISM not only assumes transitivity, but never addresses many potential connections. When it finds a cycle it chooses a proxy element and all connections to any element in the loop are shown as connections to the proxy element. Connections to the other elements must be added (and possibly subtracted from the proxy element later) to correct this problem, a task which may be more difficult than developing a causal digraph from the outset.

Our experience indicates that a certain conservatism affects ISM users. Whereas "yes" denotes a clear relation between elements, "no" is often given as a response when there is simply an absence of such a clear relation. The resulting digraph may prove difficult to convert to a causal digraph. In any case, we know of no reliable shortcuts to the development of a causal digraph, nor do we know any reliable means to convert a digraph to the appropriate causal digraph for the same situation.

6. *Selecting the appropriate SM tool among the seven.* ISM and SPIN are most useful in dealing with a large number of elements. Both are easy to use.

KSIM is more useful when there is a small number of highly aggregated variables. It is relatively easy to use.

QSIM and ELECTRE are also useful and provide credible results, but their spectrum of versatility is narrower.

IMPACT is easy to use and may lead to some insights, but the results are less credible.

Figure 14 is a guide for selecting SM tools. We remind the reader, however, that SM encompasses many other tools (cf. [7]). Their exclusion here is not meant to imply that they are useless.

#### **Needed Work for Improved Use of SM in TA**

A few researchers, such as Harary et al. [4], Warfield [6, 11, 39], Roberts [5], and Cearlock [10], have pushed to some depth—but the preponderance of labor in the field has been quite superficial.

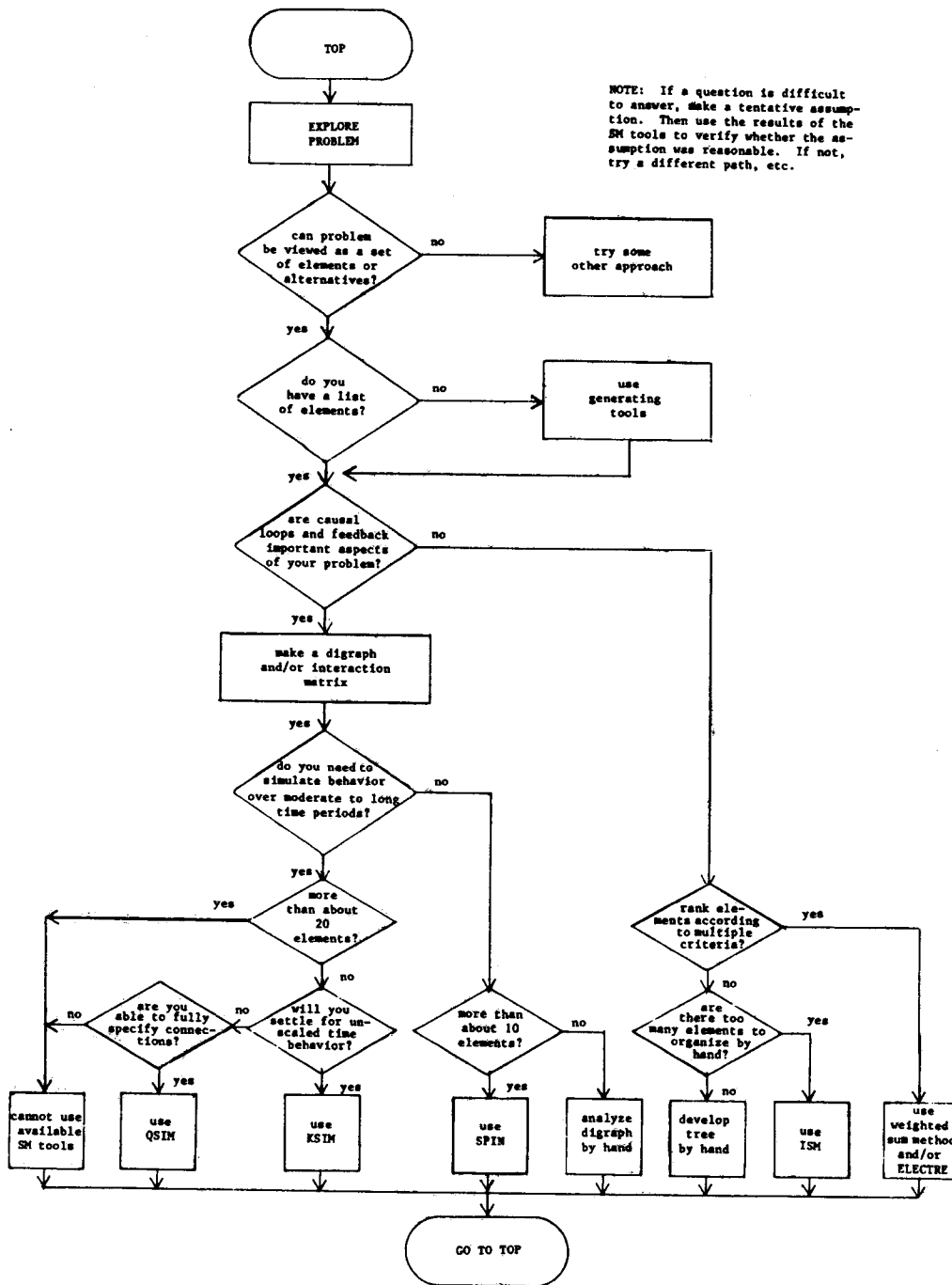


Fig. 14. Guide for choosing among the recommended SM tools.

#### BETTER DOCUMENTATION

A detailed workbook is needed which describes step-by-step how to build a structural model and how to use specific SM methods. It must also provide examples. The workbook should be oriented toward manual analysis and not push the user to rely on computers in every application.

#### A SUPERSTRUCTURE

The model builders have presented us with a plethora of tools which confound the nonexpert! Often only the tool developer is able to implement and apply the latest version. It reminds one of the "planned obsolescence" principle pioneered by Alfred Sloan of General Motors. Part of the problem has been the lack of coordination among structural modelers:

The history of use of structural models is one of lack of communication, lack of cumulation of knowledge, and inadequate sharing of experience. This is particularly well illustrated by the history of development of KSIM, on the one hand, and QSIM on the other. As originally developed, each had shortcomings. Each was further refined to overcome these shortcomings. As a result, we have a proliferation of models, each with its own users and its own peculiarities, and no general knowledge in the community of what a good model ought to look like [42].

One way to ameliorate this dilemma would be to design and implement a superstructure that would provide common input, storage, editing, and output functions for all the algorithms. This superstructure would help to reduce the redundant capabilities of the present tools and procedures, and improve the human-machine interface. (SPIN, which is far superior to any of the other tools in this respect, could serve as a model for this design.)

In addition to the data management duties, the executive routine of the superstructure could also act as an interactive conversational "front-end" implementation of Figure 2, asking the user what assumptions he or she is willing to make, and what level of information he or she is ready to supply to the model. This conversation with the front-end software would help in selecting a suitable algorithm.

Another feature that could be built into this integrated structural modeling software package is a random number generator, along with an automated rerun of the model with new random numbers. This would provide the user with a chance to run the structural models in a Monte Carlo mode, which would yield a probability distribution of outputs, which at times would be more appropriate to SM (given the uncertainty of judgments that go into a structural model) than the single output which all the tools now yield.

Algorithms could be added to the library. System dynamics could be included and serve as an end-point for those desiring to take their modeling efforts all the way through to dynamic modeling.

#### IMPROVEMENT OF EXISTING TOOLS

Research to improve the human engineering of ISM and SPIN is desirable. Better group input and graphical output techniques are needed.

Integration of SPIN and QSIM to develop their interactiveness is desirable. For example, a computer program could query the user to establish additional information: which variables are auxiliary? Are sophisticated couplings between variables needed? In this way credible time trajectories can be produced in addition to the initial structural analysis.

*Causal graphs.* Methods are needed to develop a causal graph which represents a specific system or problem. One approach is to develop a transitive digraph using ISM and then to convert it to a causal digraph. Research may determine whether a conversion process can be specified and automated. Once a causal digraph is available, it may be possible, according to current research, to use automated methods for creating a dynamic model [41].

*Stability and resilience.* Our understanding of the effect of new technology on the domains of stability of societal systems is minimal. Measures of resilience need to be developed and the safe-fail concept [37], of great significance for TA policy analysis, must be placed on a firm footing.

#### HUMAN-MACHINE INTERACTION

One of the most promising new possibilities in connection with SM is a procedure for human-machine interactive structuring. Using a lightpen, a sketch of the digraph of the system is entered on the terminal. The computer requests necessary parameters and initial conditions, performs the appropriate mathematical operations, and displays the results on the terminal [42]. We are reminded that:

The computer can give the individual a new ability to play with very complex systems, to get the "feel" or experience which he relies upon to comprehend complex systems. We refer to an informal, intimate dialogue, the concretization of *Gedankenexperimente*. The key is the use of multiple sensory modalities in interacting with the computer (manual-visual, audio-visual) [43, p. 57].

#### NEW STRUCTURES

Perhaps the sharpest blow which can be leveled at SM is its pre-occupation with a minute class of representations—trees, digraphs, networks, matrices. They suggest a woeful lack of imagination, a creature in flatland unable to conceive of more than two-dimensional space. Why should so many systems be reduced to digraphs? Are they the only simple structures we can envision? Complex systems practice self-organization and create new structures; a spiral or a helix with few elements might tell us more than a hierarchy with many [3, p. 258].<sup>13</sup> Prigogine's "order through fluctuation"<sup>14</sup> and Holling's work may be leading us toward structural modeling more appropriate to complex human systems. We suspect that the societal and behavioral perspectives on TA [28] require modeling tools of a different genre. There may be 100 structural modeling tools,

<sup>13</sup> Actually the emphasis on hierarchical structures strikingly reflects a thought pattern characteristic of Western culture. And the limited range of structures considered underscores the dominance of the principle of homogeneity. More attention to other cultural patterns, based, for example, on heterogeneity and mutual causality, should generate quite different structural models—see the work of M. Maruyama [3, pp. 142, 260].

<sup>14</sup> Fluctuations lead to unpredictable changes (analogous to biological mutations) which create a new, stable, and very different—possibly more advanced—system structure. With time, fluctuations may begin again, become more pronounced, and repeat the cycle. Such evolutionary, self-organizing processes should be of utmost significance, but cannot be analyzed with today's SM state of the art.

but there is a large, possibly dangerous, lack of tools suitable for a wide spectrum of the problems TA should address.

### A Final Thought

The carpenter uses a hammer as an extension of the arm. Structural modeling serves as an extension of our mind in thinking about complex system behavior in TA. Thinking is "a means to reach intuition," but it is neither knowledge nor wisdom—a vital distinction which all too often is not recognized, with unhappy results for the SM user.

Thinking is enhanced by the organizing, analyzing, and communicating functions of SM. Even a crude model may prove useful: a quick and inexpensive means of probing can become very cost-effective in the right hands.

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