Eliciting Group Knowledge for Model-Building

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Abstract

System dynamics models are typically created using multiple streams of information including quantitative data, written records, and information contained in the mental models of both individuals and groups. While qualitative sources of information are widely recognized as important in all stages of the model building process, little systematic research has been completed on how best to elicit and map this knowledge. In this paper, we survey the existing literature on mapping and eliciting knowledge for system dynamics modeling and also explore the literature in the broader fields of cognitive psychology and small group processes. Special attention is paid to new software advances to support these processes.[2]

The Problem

System dynamics modelers typically rely on multiple, diverse streams of information to create and calibrate model structure. Such streams include quantitative data, written records, and information contained within the mental models of key actors in a system. This last class of information is typically most helpful to set the system boundary, define the dynamic hypothesis, postulate detailed structure, and calibrate system parameters.

Commonly, the techniques for drawing out germane and accurate information are informal and highly intuitive. Accessing the most productive source of information for model- building, the minds of experts and actors in the system, is largely an art in our field. Rarely does the academic preparation of modelers include training or exposure to academic literature that helps to

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build formal skills in eliciting information for model building. Rarely do practitioners have the time to experiment with different approaches for mapping knowledge. But practitioners know that the arts of knowledge elicitation and mapping are subtle, and can be particularly complex when the modeling process calls for drawing information out of groups of people rather than individuals.

Yet in other fields more or less related to system dynamics, there already exists considerable literature that casts light on the modeler's information-gathering task. And increasingly, a number of system dynamics practitioners have begun to explore variations on the intuitive model development process described in our literature. This paper explores these developments in an effort to push forward our understandings of productive processes for eliciting knowledge that helps define problems, conceptualize structure, and develop formal models for policy analysis.

To establish a common ground for the discussion, we first review the existing system dynamics literature on knowledge elicitation and mapping, with special attention to small group processes. Next we describe several taxonomies for organizing the rest of our discussion, including distinctions among types of cognitive tasks in model-building and kinds of information sought. Finally, we discuss the various specific techniques that can help to support the knowledge and elicitation process for constructing system dynamics models.

Existing System Dynamics Literature on Knowledge Elicitation

While system dynamicists have long recognized the importance of eliciting knowledge from the mental models of individuals and small groups in the model building process, surprisingly little literature exists describing exactly how expert modelers elicit and map such knowledge.

The Informal Consulting Approach. The textbook approach to system dynamics modeling typically begins with a six or seven stage process, often with the stages coupled into an iterative process with repeated cycling among stages. For example, Richardson and Pugh (1981) define seven stages as problem identification and definition, system conceptualization, model formulation, analysis of model behavior, model evaluation, policy analysis, and model use or implementation. Roberts et al (1983) use an almost identical set of six stages to organize their pedagogical approach.

This well-defined textbook approach to modeling is virtually silent concerning how the modeler or modeling team elicits knowledge. However, the textbook approach implicitly assumes that some group of clients, policy elites, decision makers, or the public at large form an audience for a modeling effort. In fact, precise identification of the model's audience is an important step in the problem definition stage.

Consultants and others working with clients over the years have evolved very effective strategies for working with clients, often in small groups, to insure that client preferences are well integrated into the model building process. A modest body of literature documents the experiences of these seasoned modelers in their interactions with decision makers. In his paper on implementation, Roberts (1977) stresses the importance of working closely with client groups and posits a series of informal rules for working with them in various stages of the model building process. Weil (1980, 1983) continues this line of work by developing a more elaborated process model for involving groups of decision makers in the model building process. Forrester and Senge

(1980) propose a number of specific tests that can be performed to increase confidence in a model. Implicit in their remarks is the notion that some group of people would systematically evaluate model structure and behavior. However, Gardiner and Ford (1980) have demonstrated that individual decision makers can and do differ sharply in their evaluations of which policies are better and which are worse. Working on a related problem, Rohrbaugh and Andersen (1983) have shown that individual preferences or objective functions can lead to dramatically differing evaluations of a system's performance over time.

All of this literature has in common an implicit call for the modeler to work with groups to elicit and map knowledge of various sorts--knowledge about problem definition, knowledge about how much structural detail to include or exclude from a model, knowledge about model evaluation, and knowledge necessary to evaluate and rank policy options emerging from the model. Yet this literature stops far short of suggesting productive ways of working with groups to carry out these tasks.

Reference Groups and Other Structured Group Approaches. A smaller body of published work suggests some hints as to how the modeler should work with groups of decision makers in eliciting and structuring these various types of knowledge. Randers (1977) proposed the use of reference groups to support the model building process. Working primarily with public sector problems, he suggested methods for structuring broadly representative groups who will work with a modeling team through all of the phases of the modeling work sketched above to achieve consensus. Stenberg (1980) elaborated on Randers' earlier work and presented a complete process model for assembling and working with reference groups to support the modeling process. Both of these works are noteworthy because they begin to get at the "hows" of working with groups to support the model building process. However, once the group has been assembled and put on to a specific task, the implicit assumption is that good modelers are also good group process consultants and will handle a group skillfully in eliciting various types of knowledge necessary to build, test, and evaluate a model.

Recently, system dynamics modelers such as Richmond (1987, 1988) and Richardson (1988) have begun to experiment with the reference group approach by using new software products such as STELLA to get groups of decision makers to interact more directly with a model's structure and output as the model is being developed. In his work, Richardson had considerable success in separating the role of the professional modeler, who sat in the back of the room and operated a STELLA-based model being projected for review by the group, from that of a professional group facilitator who managed the group. This group facilitator was familiar with system dynamics modeling but brought generic group facilitation skill rather than system dynamics modeling skill to the overall group process.

Finally, Vennix (1989) has proposed a significantly more detailed process for working with relatively large groups in the public sector to build dynamic simulation models. Using a more fine-grained appreciation of group process, Vennix proposed that different techniques be used to support different group tasks in the model building process. He carefully designed small group exercises to match the group process to the exact task facing the group.

Once specific group process models such as these have been proposed for working with small groups, researchers can systematically evaluate the "fit" between the specific group technique proposed and the outcome of that group process. Fortunately a rich body of small group process literature already exists, much of its focused on using small groups to elicit knowledge for formal models.

Types of Tasks in Eliciting and Mapping Knowledge

The process of constructing a system dynamics model involves a wide variety of conceptual activities. For example, the process of "brainstorming" variables that may be included or excluded from the model's boundary is very different from the more detailed task of agreeing upon specific parameter values, which in turn is very different from the cognitive task of identifying the important feedback loops within a system.

Psychologists specializing in cognitive processes have commonly distinguished between three general types of tasks: eliciting information, exploring courses of action, and evaluating situations. Hackman and Morris (1975; Morris 1966; Hackman, 1968) referred to these "intellective" tasks as production, problem solving, and discussion. Bourne and Battig (1966) labeled similar "thinking" tasks as conceptual behavior, problem solving, and decision making. Simon (1960) identified the three principal activities of management with parallel terms--intelligence, design, and choice--and attributed the trichotomy to Dewey (1910).

Eliciting Information. The creation, generation, or evocation of information results in the development of a new data base for a group. Such production tasks typically are accomplished as individuals pool their ideas, insights, or experience. The terms "brainstorming" or "divergent thinking" have often been applied to some conceptual behavior of this sort. In the system dynamics model building process, this type of thinking is often most necessary in the problem definition or model conceptualization phases where an individual or a group is attempting to determine what factors or variables to include or exclude from a system's boundary, or in the model evaluation phase where the group is brainstorming how to design or evaluate a model's performance. In addition, this eliciting process may also be evoked during some phases of the model formulation process where several different formulations need to be considered.

There is considerable evidence that work on elicitation tasks in group settings should be performed by noninteracting, "nominal" groups, rather than with full discussion and exchange of ideas in an open forum (Lamm and Trommsdorf, 1973). The implication for modelers is that elements of problem definition and model conceptualization with groups is best accomplished by eliciting information from individuals and then pooling the results.

Exploring Courses of Action. Solutions to problems are discovered through devising, specifying, or following combinations of procedures that might achieve specific objectives. Problem solving within the context of the system dynamics modeling processes involves tasks such as specifying the feedback paths to be included within a model or devising a specific rate formulation. In general, problem solving produces the invention or design of multiple alternative explanations for the functioning (or disfunctioning) of a partially understood system, or the formulation of answers by diverging as little as possible from seemingly appropriate and well-known rules.

Often referred to as a form of "convergent thinking" such group activity is thought to be at its best when organized and highly systematized. However, the paucity of rules specifying what constitutes key information or what is the essential information to be structured typically makes this type of a task most puzzling to organize for a group. Deep knowledge of the system being studied and the nature of the model building task at hand is necessary to structure appropriate group activities. That is, the most critical phases of model conceptualization and formalization will be very difficult to support with group techniques unless the group is led by a skilled facilitator with significant understanding of the model building process.

Evaluating Situations. The most common modes of evaluation are judgment (assessing individuals, objects, or events one at a time on some scale) and choice (selecting one or more individuals, objects, or events from a set). In the process of building system dynamics models evaluation includes tasks such as selecting parameters, assessing the validity of model output, assessing the performance of various policies, choosing between alternative structural formulations, or choosing which policies to investigate within the context of model simulations. In both judgment and choice, evaluation is based on the explicit and/or implicit use of one or more cues that inform the group in completing its task. Judgment and choice processes do not necessarily lead to the same conclusions, however. Preferences expressed in one mode may be reversed in the other (Lichtenstein and Slovic 1971, 1973). Finally, Hammond et al (1977) and Rohrbaugh (1981) have proposed using specific techniques such a social judgment analysis to support evaluation tasks.

Table 1: Sources of Knowledge in Model Building and Techniques to Elicit that Knowledge with Relative Advantages (+) and Disadvantages (-)

Sources of Knowledge	Methods and Techniques	Advantages (+) and Disadvantages (-)
Written Documents	Content Analysis	(-) Often not written for the purpose of modeling (+) Tend to be unambiguous (+) Can be analyzed repeatedly
Individual	Interview	(+) Can be quite thorough (-) No discussion between members of management team
	Questionnaire	(-) Slow in comparison to interview (+) Less time consuming (for modeler) than interview
	Workbook	(+) Allows dealing with more complex models than questionnaire (-) Respondent cannot ask questions about unclear issues
Groups	Brainstorming	(+) Many different ideas can be generated (+) Much discussion between participants (-) No better than individual work for problem solving
	Structured Workshops	(+)Discussion strongly focused and structured (+) Allows many persons to participate (-) In general, not good for eliciting

Sources of Knowledge and Methods to Extract Them

While different types of cognitive processes are involved in various stages of the model building process, Forrester (1980) has noted that a wide variety of sources of knowledge must be incorporated into the model-building process. These sources of knowledge range from quantitative data to written documents to the mental models of both individuals and of groups.

Table 1 presents in summary form the sources of knowledge with which we shall be concerned here, techniques to be used to elicit that knowledge, and the advantages and disadvantages of these various techniques. As shown in Table 1, the range of techniques that can be used to elicit knowledge from each of these primary sources is quite varied, ranging from content analysis of written documents to interviews, questionnaires, and workbooks used by individuals to brainstorming and structured workshops used with groups. All of these approaches may be supported by special software tools. In the sections below, we review the range of specific techniques that may be useful in supporting three different types of thinking in the model building process by small groups, by individuals, and in the review of written documents.

Extracting Knowledge From Written Documents

A number of informal techniques are commonly used by system dynamics model builders to capture knowledge about system structure and behavior from written documents. However, several more formal techniques broadly grouped under the heading of content analysis can support this process. For example, Axelrod (1976) has proposed a series of specific procedures for creating "cognitive maps" of policy makers by a formal and critical analysis of documents that they have written. Following strictly specified rules, researchers code written documents in search of causal connections. When these coded statements are analyzed within a more general framework, cognitive maps, strongly resembling causal loop diagrams, result. The content coding rules have been so fully specified that two independent coders will derive very similar cognitive maps from the same written documents. Axelrod's basic approach can be applied to reconstruct from public policy documents what Hoogerwerf (1984) calls a "policy theory", the total set of assumptions underlying a specific policy. A disadvantage is that policy documents are generally not written for the purpose of modeling and frequently contain only partially relevant information for a modeler.

To overcome this apparent disadvantage, Vennix (1989) has suggested that the method developed by Axelrod can be used to extract system structure from written documents drafted by policy makers specifically for modeling the policy system. These policy notes are subsequently coded to extract the implicit "mental policy models" participants. Next a system dynamics modeling process is started, which might take these policy notes and the extracted mental policy models as its point of departure. This procedure not only allows extracting basic knowledge and a preliminary model structure from participants; it also puts the modeler in a position to establish the impact of a modeling effort on the participants' mental models. After the modeling effort is finished, the participants can be asked again to draft policy notes, which can be coded as before to extract their mental policy models. By systematically comparing these mental policy models before and after the model development process, Vennix is in a position to measure, in part, the impact of the modeling process on the thinking processes of key participants.

Eliciting Knowledge From Individuals

The consulting approach to model building relies heavily on informal discussions with key participants within a system to elicit a wide variety of information relevant to the model building process. In addition to informal discussions, there are basically two formal techniques that may be used--interviews and questionnaires. A great body of literature in the areas of sociological and ethnographic research (Hyman 1954; Riley 1963, Galtung 1969, Babbie 1979) treat these two types of techniques in exhaustive detail, and we shall not review all of it here. Suffice to say, interviews can cover a wide range from very structured to virtually unstructured. Unstructured interviews take the form of open-ended conversations. Additional structure is introduced when the modeler presents certain well thought-through questions to guide the conversation. At an even more structured level, the modeler might actually try to construct causal loops of system flow diagrams and have the interviewee participate in the system conceptualization process.

Questionnaires too can be more or less structured, but open-ended questions are usually more suitable for focusing on complex structures. Vennix et al (1988) proposed using a "model construction workbook" as an alternative to an open-ended questionnaire. This type of workbook can be conceived of as a written interview. When open-ended questionnaires are used in such workbooks, some kind of content analytic procedure such as those discussed above may be employed in order to uncover the causal arguments being made by the respondents.

Eliciting Knowledge From Groups

While system dynamicists are interested in using groups to construct, test, and interact with models, researchers studying small group processes have long been interested in many of the more general properties of small groups working in problem-solving situations. Some of the conclusions of this long line of research are summarized below.

General Comments on Group Process. McGraw and Harbison-Briggs (1989) have demonstrated that the type of knowledge and the quality of judgements acquired from experts in a group setting differ from information obtained when they are questioned as individuals. Shaw (1932) found that one advantage of using groups was their ability to recognize and reject incorrect or impossible solutions and suggestions. Steiner (1972) has found that a group of experts may be better able to solve a problem than individuals working alone when the task can be subdivided into related tasks and the expertise of each matched with a particular sub-task.

The effectiveness of groups seems to be correlated with group size, the structuredness of the process, and the type of task. Formal brainstorming techniques have been helpful in large groups but of little use in small groups. Communication among group members decreases as the size of the group increases. Slater (1958) has found that for tasks involving decisions based on evaluation of exchanged information, groups of five or fewer are most effective. Bouchard (1969, 1972) indicates that introducing structure in group sessions drastically improves group performance. Hart (1985) also points out that without structure, participants in a group can become frustrated and group performance can rapidly deteriorate. Moreover, freely interacting groups can be swayed by strong personalities and may rapidly narrow their focus to a few approaches or unduly concentrate on evaluating ideas.

Recognizing the wide variety of structures, tasks and circumstances facing groups, various sets of formal procedures have been developed for eliciting knowledge from groups. Prominent among these are nominal group techniques (Huseman 1973), Delphi techniques (Linstone and Turuff 1975), and social judgement analyses (Hammond 1975).

Using Group Process to Support System Dynamics Model- Building. It is thus useful to make a distinction between strongly or weakly structured group processes for model-building. Less structured group processes are the approaches used by most system dynamicists working in a consulting mode, but they have significant disadvantages. More structured approaches can be approached in at least two different ways. The modeling process can be broken into small sequential steps, or the group can be presented with a preliminary model that can be discussed systematically one part at a time.

An example of the first type of structured workshop is Duke's technique (Duke 1981, 64) for designing a gaming simulation. The process begins with a brainstorming session in which participants write down on small pieces of paper all kinds of concepts that come to mind when thinking about the policy problem under study. Duke calls these little pieces of paper snowcards. The second step is to organize and classify these concepts into broader categories by removing duplicate concepts, merging similar concepts, and classifying groups of concepts. The third step involves constructing a diagram of system structure using these broad categories. Differing specific small group techniques are used to support each of these small steps within a structured group workshop.

Vennix (1989) and Hart (1985) present examples of structured workshops using the preliminary model approach. In this approach the modeler first designs a preliminary model, which is then presented to the client for comment, criticism, and revision. This discussion can itself be structured, e.g., by first focusing on the concepts in the preliminary model, then addressing relationships, and finally discussing feedback loops. A clear advantage of the preliminary model approach is that it drastically limits the client's time investment. Whether a preliminary model can generate unwarranted acceptance or even distort clients' perceptions of the real system has not, to our knowledge, been investigated.

Effectiveness of the group process in either of these approaches can also be increased by having participants do some homework. "Divergent thinking" tasks are best be done by individuals, perhaps working with questionnaires or workbooks, before the actual group session.

Hardware and Software Supports for Knowledge Elicitation

Even as a large literature is beginning to emerge on how individuals and small groups approach problems and structure knowledge for problem solving, a wide variety of hardware and software supports have been developed to support brainstorming, idea sorting, and problem structuring. These software and hardware innovations may be characterized as those primarily designed to support an individual working on a personal computer or work station and those designed to support an interacting group.

Supports Designed for Individual Use. Many software and hardware supports for model building are primarily designed for use by a single expert or analyst working at a terminal or work station. It is important to note that some of these software tools are being used with groups by having output projected for review and discussion by a group as a whole. Hence, many of the visually oriented supports discussed below can be used by groups with the simple addition of an overhead projection pad for computer output.

Most system dynamics practitioners are by now familiar with STELLA as developed by Richmond et al (1988). Developed exclusively for Macintosh machines, this very powerful model building tool allows modelers to create models at a conceptual level very different from what had been possible previously using conventional simulation languages such as DYNAMO and DYSMAP. Using STELLA, analysts work with screen oriented icons that allow them to construct system flow charts interactively. After users respond to several prompts and queries at key decision points (usually rates and auxiliaries), the STELLA system automatically creates simulation code and can then execute a simulation, with a standard animated mode possible. However, as a general rule, persons expert in a policy problem with little or no background in modeling will not be able to interact directly with STELLA, at least initially. Typically, when STELLA is being used to structure group discussions and interactions in the model development process, a modeling expert must be present to help substantive experts interact with STELLA and the models that are created using this language.

Diehl (1988) and Richmond (1989) have developed gaming interfaces for STELLA. Using these interfaces, modelers may create an animated game-like view of a simulation. Using these animations, users may interact directly with the simulation model, often without having to come to grips with or understand the structure of the system under study. (Such a facile ability to interact with a model has both positive and negative implications.)

Modern versions of DYNAMO contain front end packages that allow users to interact more easily and directly with a simulation model once it has been created. Using a structured and menu-driven series of screens, users respond to a series of queries and the package creates a stream of commands much like the traditional RERUN streams that creates a new model run. Packages such as these are very useful for allowing users to interact with a model once it has been constructed. Expert modeling support is needed to construct both the model and to program the front-end package.

A variety of software packages exist for supporting individual or group brainstorming sessions. For example MAXTHINK (IBM compatible) or MORE (Macintosh) provide a set of flexible text processing and sorting utilities than can help to both elicit and organize verbal concepts. Working in one mode the user can create a list of unstructured verbal phrases. Working in another mode within the software, these phrases or concepts can be sorted and grouped into similar "bins" and reworked or ranked. When projected in front of a small group, these software programs can be used to support group brainstorming, acting as a sort of infinitely flexible "electronic flip-chart".

Shachter (1986) has developed DAVID, a modeling tool that helps to structure influence diagrams and representations of probabilistic and deterministic decisions. DAVID can be used as a software support in the conceptualization or problem definition phases of a modeling project where causal loops are being either generated or discussed by a group. DESIGN on the Macintosh can be used similarly. The potential of these software tools for model conceptualization in groups has, to our knowledge, not yet been tested.

Hardware and Software Designed to Support Interacting Groups. Recently, a number of sites have experimented with multiple, linked work stations or terminals designed to support knowledge elicitation. While these facilities have never been used to support the construction of system dynamics models, their existence and general capabilities should be discussed because of possible future utility of such facilities.

Electronic support for group activities have been carried out in a variety of places. The two most well known are at the decision and planning laboratory at the University of Arizona and at Xerox Park's COLAB. Arizona has a research facility for studying the impact of automated support for planning and decision-making. It is used by executives, managers, and students for planning sessions and to address complex, unstructured decision processes. As described by Nunamaker, Applegate, and Konsynski (1988) the lab has been operational since March 1985 with state-of-the-art computer hardware and software used in a boardroom. Two of their software tools are used to support the process of deliberation, electronic brainstorming, and stake-holder identification and analysis. Electronic brainstorming permits participants to network using micro-computers to share comments and contributions with other participants. Comments from all participants are consolidated and an analysis support tool is used to identify common issues or categories. This computer-based technique is adapted from manual procedures developed in association with Strategic Assumptions Surfacing and Testing as reported in Mason and Mitroff (1981).

The use of dynamic interactive media at Xerox is part of COLAB. This computer lab's purpose is to increase the effectiveness of meetings and to provide a research environment to investigate the effects of computer tools on meetings. Stefik et al (1987) report that within COLAB a variety of tools are available to provide participants with a coordinated interface, enabling them to interact cooperatively. COLAB tools support simultaneous action, allowing group members to work in parallel on shared objects. Conflicts, (e.g., more than one member attempting to act on the same image) are handled by a busy signal. There are a variety of software tools to extend the uses of COLAB.

Both the Arizona and the Xerox labs can be seen as experimental mechanisms for eliciting the group knowledge useful in model building. However, their effectiveness in designing models is as yet to be assessed.

Implications: When to Select Which Technique

Several factors help the modeler to select appropriate knowledge elicitation techniques--the type of task being performed, the number of persons involved in the process, the purpose of the modeling effort, the phase of the modeling effort, the time available for participants, and finally the costs involved in using various techniques.

Type of Task. From a psychological point of view, eliciting, exploring, and evaluating tasks need to be approached very differently. Eliciting tasks, whether performed by individuals or groups require divergent thinking. These tasks are additive, that is, the largest list of alternatives can be generated simply by adding up the contributions of individual contributions. Performing these tasks in the context of well-structured group interactions will actually decrease the quality of group versus individual performance. For example, a discussion designed to elicit an exhaustive list of variables that might be included within a model's boundary should not be performed by a whole group; rather, individuals should make a list working alone and the group facilitator should merely compile these individual responses.

The literature on evaluation, whether it involves individual or group evaluation of options, events, or alternative formulations, is quite well-developed. Specific techniques such as the Delphi technique (Linstone and Turuff 1975), social judgment analysis (Hammond 1975), and nominal group techniques (Huseman 1973) have well developed theoretical underpinnings and have been well-explored in experimental settings. When client groups are involved in evaluative tasks--selecting parameter values, evaluating alternative structural formulations, or assessing model validity or the policy performance of a model--system dynamics modelers must base their work on the accumulating research results in the field of individual and group judgment.

The exploring (problem solving) task is both most central to the model building process and least well- developed in the psychological literature. Some evidence suggests that well-trained or knowledgeable individuals can perform as well as or even better than groups. A well-trained model builder can do as well as a group of model builders in tasks such as proposing formulations or designing feedback structures. Involving a group may have an apparent purpose of designing model structure, but have as a real purpose developing understanding of the system under study or of the model-building process.

Number of Persons. The number of persons ultimately to be involved in the modeling project will dictate the appropriate knowledge elicitation techniques because of two factors. First, the fewer the number of persons involved, the more unstructured the techniques may be. On the other hand, the larger the number of involved people (as in public policy modeling), the more structured the approaches must be to prevent discussions from getting out of hand. Second, as more people become involved in the modeling process, it becomes necessary to use labor-saving techniques such as questionnaires, workbooks and structured workshops.

Purpose of the Modeling Effort. The process of eliciting and mapping knowledge to build system dynamics models is iterative--through successive cycles of refinement the ultimate model gradually appears. This indicates that the process of modeling involves considerable learning and improvement of communication between members of the management team. So knowledge elicitation and mapping is not simply a process of uncovering a fixed body of knowledge and representing it. Participants learn, as their mental models are reshaped by discussion and interaction.

This iterative view of the knowledge elicitation process has profound implications for the methods and techniques to be used. First, in general the knowledge necessary to model a problem will not be readily available. Rather the modeling effort often uncovers gaps and inconsistencies in existing knowledge and mental models. One cannot rely on techniques that aim solely at capturing and representing knowledge (such as content analysis). Modelers will have to employ methods that allow interaction and discussion in order to improve mental models and to clarify a problem.

The second implication, following as a consequence of the first, is that modelers will have have to employ methods and techniques that will enhance learning and communication among members of the management team. One cannot rely solely on techniques that use written documents or the individual as the only source of knowledge. In modeling policy problems, groups as a source of knowledge will almost always have to be included in the modeling process.

Phase of the Modeling Process. As a general rule, each phase of the model-building process tends to be dominated by a single type of cognitive task and hence is most appropriately supported with specific knowledge elicitation techniques. For example, the problem identification and system conceptualization phases are dominated by elicitation tasks, the model formulation phase by exploring (problem solving) tasks, and the model analysis and model evaluation phases by evaluating tasks. As a general rule, less structured techniques tend to be more appropriate for the earlier phases of the model building process (where thinking is more divergent) and more structured techniques more appropriate for the later, more convergent phases.

However, even this general rule of thumb can be deceptive. Consider a model conceptualization exercise designed to get at the issue of model boundary. A first phase of that exercise might involve brainstorming variables to be included or excluded from the model's boundary. This eliciting task would probably be best performed in a nominal group by individuals working alone, with the group convened to sum up all responses generated. However, as a second step, the group as a whole might be asked to evaluate which of the variables elicited are most important and need to be retained as the model is developed. Obviously, this would be a more structured evaluative task.

Hence the phase of the model building effort interacts subtly with the type of cognitive task being undertaken in determining what type of knowledge elicitation techniques are most appropriate in a given specific situation. In each phase of the modeling process various techniques may have to be employed in combination, depending on the type of task that has to be performed.

Time Available for Participant Discussion. A simple but powerful criteria for determining what knowledge elicitation techniques to use is how much time does the management team or reference group have to spend on task. The less time that they have available for active participation in the modeling effort, the more the process will have to be carefully structured. For example, a group might begin with a preliminary model rather than attempt to develop a model from scratch.

Cost. Finally, the costs associated with the various techniques must be carefully factored into the selection of knowledge elicitation and mapping techniques. Costs include participant costs (usually in terms of time devoted to the modeling process) as well as the costs of time for the modeling team. Usually costs (both monetary and time costs) will be negotiated at the beginning of a project and the modeler's task will be to select the best techniques given cost constraints. Hence cost considerations are most important at the stage where a modeling contract or agreement is being designed. In one innovative approach of which we are aware, a modeler uses group facilitation techniques in order to help management teams decide early on how much of their time and funds they wish to expend on a specific modeling project.

Summary and Directions for Future Practice and Research

A rich body of theoretical and experimental work already exists on how to elicit and map qualitative knowledge that resides in written documents, as well as the mental models of individuals and groups. An interesting array of software products is beginning to emerge to support such model-building exercises. Yet most of these techniques and advances seem not to have penetrated into the system dynamics literature. It seems clear that those who write about the system dynamics modeling process are not paying close attention to developments in other fields that hold great promise for improved system dynamics practice. Similarly, those most experienced in the art of modeling appear not to have the time or inclination to write down the lessons that they have learned from years of practice working on knowledge elicitation and mapping.

As a result, the critical phases of problem definition and model conceptualization appear to be arrested at the point where they remain true art forms. Simply put, systematic research is not being conducted that will advance our understanding of how modelers and management teams or reference groups do or ought to interact in the model building process. This lack is all the more disturbing because psychologists, ethnographers, management scientists, and software engineers working in fields closely related to system dynamics are making progress in precisely these fields. The field of system dynamics needs to begin the work of formulating rigorous research programs that get at general rules helping to make more precise and less artful the process of eliciting and mapping knowledge.

References

Axelrod, R. 1976. *Structure of Decision: the Cognitive Maps of Political Elites.* Princeton, NJ: Princeton University Press.

Babbie, E.R. 1979. *The Practice of Social Research.* Belmont, CA: Wadsworth Publishing.

Bouchard, T. 1969. Personality, problem solving procedure and performance in small groups. *Journal of Applied Psychology* 53: 1-29.

Bouchard, T. 1972. A comparison of two group brainstorming procedures. *Journal of Applied Psychology* 56: 418-421.

Bourne, L. E., and W.F. Battig. 1966. Complex Processes.. In J.B. Sidowski, ed., *Experimental Methods and Instrumentation in Psychology.* New York : McGraw-Hill.

DESIGN. Meta Software, 150 Cambridge Park Drive, Cambridge, MA 02140. Reviewed in Mac User. April 1988.

Dewey, J. 1910. *How We Think.* New York: D.C. Heath.

Duke, R. D. 1981. A paradigm for game design. In C. S. Greenblat and R. D. Duke, *Principles and Practices of Gaming-Simulation.* Beverly Hills: Sage.

Edwards, W. and J. R. Newman. 1982. *Multi-Attribute Evaluation.* Beverly Hills: Sage.

Forrester, J. W. 1980. Information Sources for Modeling the National Economy. *Journal of the American Statistical Association.* Vol. 75, 371: 555-574.

Forrester, J. W., and P. M. Senge. 1980. Tests for Building Confidence in System Dynamics Models. *TIMS Studies in Management Sciences.* 14 (System Dynamics): 209-228.

Fox, W. M. 1987. *Effective Group Problem Solving.* San Francisco: Jossey-Bass.

Galtung, J. 1969. *Theory and Methods of Social Research.* New York: Columbia University Press.

Gardiner, P.C. and A. Ford. 1980. Which Policy Run is Best and Who Says So: *TIMS Studies in the Management Sciences* 14 (System Dynamics): 241-257.

Graham, A. K. 1980. Parameter Estimation in System Dynamics Modeling. In *Elements of the System Dynamics Method*, Jorgen Randers, ed. Cambridge, MA: The MIT Press, 143-161.

Hackman, J.R. 1968. Effects of Task Characteristics on Group Products. *Journal of Experimental Social Psychology* 4: 162- 187.

Hackman, J.R. and C.G. Morris. 1975. Group Tasks, Group Interaction Process, and Group Performance Effectiveness: A Review and Proposed Integration. In L. Berkowitz, ed., *Advances in Experimental Social Psychology* (Vol. 8). New York: Academic Press.

Hammond, K.R., T.R. Stewart, B. Brehmer, and D.O. Steinmann. 1975. Social Judgment Theory. In M.F. Kaplan and S. Schwartz (eds.), *Human Judgment and Decision Processes in Applied Settings*. New York: Academic Press.

Hammond, K.R., J. Rohrbaugh, J.L. Mumpower, and L. Adelman. 1977. Social Judgment Theory: Applications in Policy Formation. In M.F. Kaplan and S. Schwartz, eds., *Human Judgment and Decision Processes in Applied Settings*. New York :Academic Press.

Hart, S., M. Boroush, G. Enk, and W. Hornick. 1985. Managing Complexity Through Consensus Mapping: Technology for the Structuring of Group Decisions. *Academy of Management Review* , 10(3): 587-600.

Hoogerwerf, A. 1984. Beleid berust op veronderstellingen: de beliedstheorie (Policies are based on assumptions: the policy theory). *Acta Politica*. 4: 493-531.

Huseman, R. 1973. The Role of Nominal Groups in Small Group Communication. In R.C. Huseman, D.M. Logue, and D.L. Freshley (eds.), *Readings in Interpersonal and Organizational Communication* (second edition). Boston MA: Hollbrook.

Hyman, H., ed. 1954. *Interviewing in Social Research*. Chicago: University of Chicago Press.

Lamm, H. and G. Trommsdorf. 1973. Group Versus Individual Performance on Tasks Requiring Relational Proficiency (brainstorming): A Review. *European Journal of Social Psychology* 3: 361-388.

Lichtenstein, S. and P. Slovic. 1971. Reversals of Preference between Bids and Choices in Gambling Decisions. *Journal of Experimental Psychology* 89: 46-55.

Lichtenstein, S. and P. Slovic. 1973. Response-induced Reversals of Preference in Gambling: An Extended Replication in Las Vegas. *Journal of Experimental Psychology* 101: 16-20.

Linstone, H. and M. Turuff. 1975. *The Delphi Method: Techniques and Applications*. Reading MA: Addison Wesley.

Mason, R., and I. Mitroff. 1981. *Challenging Strategic Planning Assumptions*. New York, NY: John Wiley and Sons.

McGraw, K.L, and K. Harbison-Briggs. 1989. *Knowledge Acquisition: Principles and Guidelines*. Englewood Cliffs NJ: Prentice Hall.

Morris, C.G. 1966. Task Effects on Group Interaction. *Journal of Personality and Social Psychology* 4: 545-554.

Nunamaker, J.F., L.M. Applegate, and B.R. Konsynski. 1988. Computer-Aided Deliberation: Model Management and Group Decision Support. *Operations Research* 36,6 (Nov- Dec 1988). 826-848.

Randers, J. 1977. The Potential in Simulation of Macro Social Processes, or How to be a Useful Builder of Simulation Models. Oslo: Gruppen for Ressursstudier.

Richardson, G. P. and S. Schuman. 1987. Medical Malpractice Insurance: Policy Implications and Evaluations. Decision Techtronics Group, The Rockefeller Institute of Government, 411 State Street, Albany, NY 12203.

Richardson, G.P., and A.L. Pugh. 1981. *Introduction to System Dynamics Modeling with DYNAMO.* Cambridge, MA: The MIT Press.

Richmond, B. 1987. *The Strategic Forum.* Lyme, NH: High Performance Systems.

Richmond, B., S. Peterson, and P. Vescuso. 1988. *Academic User's Guide to STELLA.* Lyme NH: High Performance Systems.

Richmond, B. 1989. *STELLAStack.* Lyme NH: High Performance Systems.

Riley, M. W. 1963. *Sociological Research.* New York: Harcourt, Brace & World.

Roberts, E. B. 1977. Strategies for Effective Implementation of Complex Corporate Models. *Interfaces* 8,1, Part I.

Roberts, N., D.F. Andersen, R. Deal, M. Garet, and W. Shaffer. 1983. *Introduction to Computer Simulation: A System Dynamics Modeling Approach.* Reading MA: Addison Wesley.

Rohrbaugh, J. 1981. Improving the Quality of Group Judgment: Social Judgment Analysis and the Nominal Group Technique. *Organizational Behavior and Human Performance* 28: 272-288.

Rohrbaugh, J., and D. F. Andersen. 1983. Specifying Dynamic Objective Functions: Problems and Possibilities. *Dynamica* 9:1.

Shachter, R.D. 1986. DAVID: Influence Diagram Processing System for the Macintosh. Working Paper, Department of Engineering-Economic Systems. Palo Alto CA: Stanford University.

Shaw, M. 1932. A Comparison of Individuals and Small Groups in the Rational Solution of Complex Problems. *American Journal of Psychology* 44 (1932): 491-504.

Simon, H.A. 1960. *The New Science of Management Decision.* New York: Harper and Row.

Slater, P. 1958. Contrasting Correlates of Group Size. *Sociometry* 25 (1958): 129-139.

Stefik, M., G. Foster, D. Bobrow, K. Kahn, S. Lanning, and L. Suchman. 1987. Beyond the Chalkboard: Computer Support for Collaboration and Problem Solving in Meetings. *Communications of the ACM.* 30,1 (1987): 32-47.

Steiner, I. 1972. *Group Process and Productivity.* New York: Academic Press.

Stenberg L. 1980. A Modeling Procedure for Public Policy. *Elements of the System Dynamics Method.* Cambridge, MA: The MIT Press.

Vennix, J.A.M. 1989. *Interactive Computer Modeling: Improving Mental Policy Models and Policy Theories.* Ph.D. dissertation: Catholic University of Nijmegen, The Netherlands.

Vennix, J.A.M., J.W. Gubbels, D. Post, and H.J. Popper. 1988. A Structured Approach to Knowledge Acquisition in Model Development. *Proceedings of the 1988 International Conference of the System Dynamics Society,* La Jolla, CA. Cambridge MA: The System Dynamics Society.

Vennix, J.A.M. 1989. *Interactive Computer Modeling: Improving Mental Policy Models and Policy Theories.* PhD dissertation: Catholic University of Nijmegen, The Netherlands.

Weil, H. B. 1980. The Evolution of an Approach for Achieving Implemented Results from System Dynamics Projects. *Elements of the System Dynamics Method: Proceedings of the 1976 International System Dynamics Conference.* (Geilo, Norway, 1976). Cambridge, MA: The MIT Press.

Weil, H. B. 1983. The Dynamics of Strategy Implementation. *Dynamica* 9,1 (summer 1983): 43-47.