The Evaluation and Development of Knowledge Acquisition in System Dynamics Studies

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ABSTRACT

An examination of knowledge acquisition techniques and knowledge representation structures used in expert system development and technology forecasting, helped to determine how to elicit information from System Dynamics analysts. In this ongoing research, insights from the literature on knowledge acquisition, combined with knowledge elicited from System Dynamics analysts, are being used to develop an approach designed to improve the knowledge acquisition processes and structures used during the problem formulation and model conceptualization activities of System Dynamics. Also, preliminary insights are presented regarding the selection of knowledge acquisition techniques and knowledge representation structures.

THE PROBLEM

Limited previous work has been done in investigating the selection and use of knowledge acquisition techniques and knowledge representation structures for System Dynamics studies. System Dynamics analysts need to obtain sufficient reliable information about many aspects of their subject systems quickly, inexpensively and unobtrusively enough so they can study and influence them to 'improve' their behaviors. They also should efficiently, accurately, and understandably communicate useable information about the system and the analysis to the appropriate system participants. A methodology for improving the knowledge acquisition process used by System Dynamics analysts should make a significant contribution to the effectiveness of System Dynamics studies by:

a) helping to establish consistency in implementing the System Dynamics process;
b) allowing the increased involvement of experts and decisionmakers, laying the groundwork for wider acceptance of System Dynamics models;
c) facilitating System Dynamics team efforts by providing standard methodology;
d) combatting the increasing tendency to view System Dynamics as simulation programming;
e) improving the quality, implementability and retention time of System Dynamics recommendations.

RESEARCH APPROACH

The System Dynamics literature was investigated regarding what is written on knowledge acquisition and knowledge representation. Then a range of knowledge acquisition techniques and knowledge representation structures from expert systems and technology forecasting were examined to determine what may be applicable to System Dynamics. There are two methods for measuring the worth of these techniques and structures. One could apply them in real System Dynamics studies and try to evaluate the differences these new techniques and structures make. This approach would be very difficult and time consuming to execute. The second method is to involve System Dynamics analysts in evaluating the worth of these new techniques and structures. This second approach should take less time, enhance communication within the System Dynamics profession, and be of more direct value to System Dynamics analysts. Having selected this second method, the next step in the overall approach was to select the elicitation techniques most effective in eliciting opinions from System Dynamics analysts. A range of expert techniques were examined. The decision was made to use the Delphi with a wide cross section of System Dynamics experts, interview local experienced System Dynamics analysts, and use a modified Nominal Group Technique with the local System Dynamics group. The results of these 3 methods are providing: 1) information on what knowledge acquisition techniques and knowledge representation structures are currently being taught and used, 2) an evaluation of these techniques and structures, 3) opinions on new techniques and structures, and 4) methods for consistent exploration and development of knowledge acquisition in System Dynamics.

KNOWLEDGE ELICITATION TECHNIQUES

Vennix (1990) elicited information from system participants regarding model development and verification. The System Dynamics team developed a model, and had a group of Healthcare system participants evaluate, revise, and verify it using a modified Delphi exercise. The exercise consisted of three parts. First, a Delphi questionnaire was distributed. It had three goals: elicit participants' opinions on concepts and relationships of the preliminary model, expand the number of concepts considered relevant to the policy problem, and reduce the number of concepts by having participants prioritize them. Second, a Delphi workbook was distributed. It contained a number of hypotheses about relationships between concepts which were visualized using causal diagrams. These hypotheses were based on the preliminary model and the results of the questionnaires. The respondents were asked to comment on the hypotheses and the causal diagrams. And finally, based on the workbook results, structured workshops were held, where the controversial concepts and relationships were extensively discussed. A final conceptual model was designed based on this modified Delphi exercise.

Richardson et al. (1989) presented a survey of work done in knowledge elicitation for System Dynamics modeling. They concluded that "problem identification and system conceptualization phases are dominated by elicitation tasks, ... less structured techniques tend to be more appropriate for the earlier phases of the model building process" (p. 354), and the selection of a knowledge elicitation technique should be based on the task at hand, number of persons involved with the process, the purpose and phase of the modeling effort, along with time and cost constraints.

Sancar and Cook (1985a) examined a set of 'cognitive criteria' to guide study participants in the problem definition phase of a System Dynamics study. In examining knowledge elicitation, they concentrated on the group discussion process, and specified criteria to guide in identifying the perspective, time horizon, and policy choices, establishing reference mode, and defining the basic mechanisms. Sancar and Cook (1985b) used these criteria to develop a decision support system for community development consisting of: 1) a generic community development System Dynamics model, 2) a problem structuring algorithm, and 3) a situational System Dynamics model.

Interpretive Structural Modeling (ISM) is central to the problem structuring algorithm. It allows the generation of a rich picture of the situation reflecting the variety in perceptions, interests, and interrelationships, without imposing any preconceived structure. ISM has three major steps:

1) List variables, and establish a relational proposition reflective of the type of variables.
2) Generate the interaction matrix. This can be done by an individual, but a group process is more effective for System Dynamics modeling. It can be done manually or electronically using an interactive computer program. Matrix entries may be evaluated by ranking and rating.
3) Software is used to generate 'directed graphs' from the interaction matrix.

The use of ISM allows "a collective appreciation of the situational context" (p.750).

While Sancar and Cook (1985a, 1985b) and Richardson et al. (1989) drew from psychology and expert systems to develop knowledge acquisition in System Dynamics, much additional work is needed. Expert system development has been one of the most profitable areas of Artificial Intelligence. It has been widely recognized that the bottleneck to expert system development is knowledge acquisition. This climate has led to a proliferation of research and literature on knowledge acquisition and knowledge engineering. System Dynamics analysts should be viewed in part as knowledge engineers who: elicit knowledge from individuals and groups involved with the system at various levels; acquire knowledge from the literature on the domain and from organizational data; and structure the knowledge to most effectively employ the principles of System Dynamics.

In expert system development, knowledge engineers are dominantly concerned with extracting expert knowledge with the goal of developing the most effective expert system. They are more concerned with the end product, while System Dynamics analysts are more concerned with the process. The System Dynamics process not only involves extracting information from experts, but throughout the study includes conveying the dynamic, causal feedback characteristics, inherent in the situation, that address the clients' concerns. The techniques of expert system development will not address all the knowledge acquisition needs of System Dynamics. However, the collective intensity applied by expert system knowledge engineers, in extracting expertise and understanding the causality behind the actions of experts, has produced a range of techniques worth examining.

Interviews are the most popular method of gaining information from system participants in most system analysis studies, and certainly the most popular method of eliciting information in System Dynamics studies. Yet, little effort is spent studying, documenting or training analysts how to effectively interview. An interview can be fully structured, semi-structured, or unstructured (Cordingley 1989). A fully structured interview is one in which the interviewer has carefully prepared in advance all of the questions to be asked. Each question is precisely worded. The questions are asked in a specific predetermined order. When multiple interviews are involved the same questions are asked, in the same order, using the same words in each interview. Structured interviews are most appropriate for surveys and large multiple interviews. Fully structured interviews allow analysts to use forms to document interviews. The potential problem with structured interviews is the limitations placed on responses and dialog by the rigid structure. In semi-structured interviews, the interviewer starts with a list of questions to be asked, but the wording of the questions and the order in which they are covered can vary. This flexibility allows the interviewer to adopt the vocabulary of the interviewee, and adjust the flow and intensity of the session to the particular conditions. Semi-structured interviews are harder to document than structured interviews, and place more demands on the interviewer, who must correctly interpret the situation and make spot adjustments. Unstructured interviews allow interviewees to cover topics in their own way. The interviewer uses starter or seed questions to initiate elicitation in a very general fashion. Prompts and probes are used to continue information flow from the interviewee. Probes encourage the elaboration on a point of interest to force a more complete answer. Prompts are used by the interviewer to change the course of the interview. Unstructured interviewing is the most difficult. It requires a skilled interviewer to allow interviewee flexibility, but prevent useless rambling. There are a number of additional approaches to classifying interview types. Numerous disadvantages to interviews were pointed out by Forsythe and Buchanan (1989). Through their tone, choice of words, or body language, interviewers may give away their opinions, attitudes, biases and expectations. This can lead to concealing of information, negative responses, and lack of cooperation on the part of the expert being interviewed.

Process tracing techniques allow the analyst to learn how the respondent solves a particular problem, completes a task, or reaches a conclusion. These techniques are effective in showing what information is used to make decisions and how this information is processed. Unlike interviews, process tracing sessions typically are not interactive. The analyst presents the particular problem, process or task. Then the expert responds until the problem is solved or the task or process is concluded. Process tracing sessions use one of two basic techniques: concurrent or retrospective verbalization. With concurrent verbalization the expert 'thinks out loud' while solving the problem, and the analyst documents the session. In a retrospective verbalization session, the expert's procedure is recorded, and later the expert and the analyst jointly review the session and produce documentation.

'Task analysis' is a method used to: 1) describe the functions an expert performs, and 2) determine the relationship of each task of a certain dimension to the overall job. 'Task analysis' information is generated for each task. Typically this includes: task title, description, and type; knowledge required to complete the task; typical, critical, and/or permissible performance times; and other tasks related to, depending on, or interacting with this task. Subtasks may be identified for each task. There are no established rules for applying task analysis. Generally form follows function. In other words, the application of 'task analysis' is domain and context sensitive.

The 'Job analysis' technique is used to identify the major responsibilities of a job or, on a broad level the tasks that a job entails. The knowledge engineer develops a list of 'task statements' that describe what someone performing the given job should be capable of doing. Job description documents, onsite interviews, observation methods, and specialized survey style questionnaires can be used to gather and compare information for task statements. The 'task statement' consist of: the behavior, conditions for the behavior, and standards against which the behavior is evaluated. McGraw and Harbison-Briggs (1989) specified alternative guidelines for developing 'task statements' in conducting a 'job analysis'.

The Repertory Grid technique draws on George Kelly's theory of personality, which is based on the notion that humans are scientists, experiencing events, perceiving similarities and differences among these events, formulating concepts or 'constructs' to order, classify and categorize events, and hence the world, and using such constructs to anticipate events (Magee 1987, p.66) The repertory grid is both a technique and a structure. It is used to represent a respondent's organization of basic concepts in a specific domain. A domain is established, then the analyst elicits a set of constructs (bipolar characteristics that typify the domain). For example, if the domain is 'decisionmakers in a firm', a typical construct would be 'level of experience'. It's bipolar values may be 'inexperienced' and 'very experienced'. After the critical constructs have been established, the analyst elicits a set of domain examples, called elements, from the respondent. Using the domain 'decisionmakers in a firm' the element list may include marketing manager and finance manager. The grid structure consists of the constructs listed along the rows and the elements listed above the columns. The respondent rates each element according to the constructs. The ratings are placed in the grid.

Protocol analysis refers to the analysis of: 1)transcripts of domain activity, 2)documentation on standards and policies; and 3) data on domain activity. Knowledge engineers use several techniques to evaluate protocols. The selection of techniques is both context and domain dependent. Johnson et al. (1987) developed a technique that is useful for a wide range of protocols. This method consist of syntactic analysis and semantic analysis. Syntactic analysis involves identifying behavior in the protocol record by category (operations, episodes, and data cues). This information is used to assign semantic categories (actions, abilities, goals, conditions, strategies, and solutions). "Syntactic analysis allows the protocol record to be partitioned into separate categories of behavior, it is the semantic analysis that forms the basis for a representation of expertise" (Johnson et al. 1987, p.165). Richardson et al. (1989 p.347) mentioned 'content analysis' as a useful method for analyzing written documents. Content analysis is a form of protocol analysis.

The original Nominal Group Technique was developed by Delbecq and Van de Ven and is summarized by the six steps listed below based on Porter et al. (1990):

Step 1: Silent Idea Generation . Each participant works silently to list factors believed to be central.

Step 2: Group Round-Robin listing of Factors: Without discussion, each participant reads one of his/her factors, which is posted for all to see. This process continues until all factors have been listed.

Step 3: Discussion and Clarification of Listed Factors: Each factor on the list is discussed informally by the group to gain clarity. Factors may be added or combined during the discussion.

Step 4: Individual Written Voting on Priorities: Each participant silently and independently selects the most important factors from the revised list generated in step 3.

Step 5: Discussion of Voting Results: The factors with the highest vote totals in step 4 are displayed. The group evaluates the result. New formulations may be produced.

Step 6: Final, Silent, Individual Written Voting: Participants select the most important factors from the list generated in step 5, without regard to the preliminary ranking.

Committees are the most common group technique in modern organization. The value of committees depends heavily on the skills of the chairperson in preparing for and conducting the committee meetings. Because committees lack anonymity, the relationship between members is a big factor in productivity. While positive relationships can inspire members, and help forge a group identity and commitment to committee decisions, a negative group relationship can result in demoralization, animosity and a totally ineffective committee.

The most common method for soliciting input from groups of experts, when meetings are impractical, is the survey. It is generally quick, easy and inexpensive. It is most popular when a large number of dispersed participants are involved. The disadvantages are failure to produce consensus or provide feedback to participants.

The Delphi procedure is a family of methods that are variations on the approach initially developed at Rand Corporation. The strengths of the Delphi procedure are anonymity, iteration with controlled feedback, statistical group response, and the ability to deal with geographical dispersion of experts. It is a special type of survey involving multiple iterations. The first round is generally more open ended. The statistical results from a questionnaire are included in the next questionnaire. The statistical treatment of responses allows portrayal of differences of opinion within the group and checking for convergence as rounds proceed. A policy Delphi is a particular variation of the Delphi method that can be used as a precursor to a committee activity. Its goal is not to obtain a consensus, but to expose all the differing positions advocated, and the principal arguments for and against each position.

KNOWLEDGE REPRESENTATION STRUCTURES

Knowledge representation has been addressed explicitly in System Dynamics over the years (Randers 1980; Morecroft 1982, 1992). Every System Dynamics study addresses knowledge representation implicitly. Knowledge representation is particularly critical in problem formulation and model conceptualization. The activities during these phases of a System Dynamics study must examine the mental models of study participants, analyze documentation relevant to the study, when possible observe the situation under study, and encourage communication among study participants with the objective of developing a shared understanding of the dynamic feedback phenomenon inherent in the situation under study that is relevant to the study problem. The visualization of knowledge is key to this process.

The most basic knowledge structure implicit in all dynamical models is the simple variable. Graphs of simple variables, as a function of time, are widely used in a range of disciplines to illustrate the dynamics of a situation. Time histories are line graphs based on real or hypothetical data, that show the dynamic nature of variables critical to the study. Graphs of variables as a function of another variable are also useful knowledge representation structures. They give a visualization of correlation between variables and are helpful in establishing or verifying causality, and in setting parameters. The generation of variable lists and tables has the advantage that the use of lists and tables is a common practice easily conveyed to study participants and study audience. Coyle (1971) used lists in the 'List extension method'. This is a list building method used to generate an influence (causal loop) diagram. More recently Wolstenholme (1990) used variable lists. Resources of importance were identified and listed, then subsequent lists were generated for each resource listing the states the resource could exist in. This set of lists can be the basis of a resource - state table.

The most popular (and most controversial) knowledge representation structure used in model conceptualization is the causal loop diagram. The strength, of the causal loop diagram, is it provides a visualization of the feedback, central to System Dynamics, with a minimum of distinct components. The drawbacks in causal loop diagrams as a conceptualization tool were pointed out in Morecroft (1982), and Richardson (1986).

Morecroft (1982) presented two tools for conceptualization: the subsystem diagram and the policy structure diagram. Subsystems represent the major organizational divisions in the system under study, and should correspond to the major units in the mental models of key system participants. The subsystem diagram should communicate an overview of the model. While more aggregated than a causal loop diagram, the distinction in the linkage makes it a richer diagramming tool. Six types of flows are used: materials, money, people, capital equipment, orders, and information. A different symbol is used to represent each type of flow. This can make it a more valuable knowledge representation structure in conveying model conceptualization to study participants, allowing participants to adjust it based on their mental models, and serving as the basis for more detailed model conceptualization.

Each subsystem can be represented by a policy structure diagram. Like a flow diagram, it identifies the stock and flow network in the subsystem. However, policy structure diagrams are simpler than system flow diagrams. Instead of including the detail of decision making, policy structure diagrams only address major policies and decision functions. Morecroft outlines a two step process for generating the linkage in a policy structure diagram. First, policy symbols are drawn to delineate the decision making responsibilities of the organization. Then, an information network is created using policies as nodes for informational links. The advantage over causal loop diagrams is "feedback structure is then created from the orderly process of piecing together multiple decision functions, rather than emerging from the more tenuous and ad hoc methods of postulating causal links independent of the underlying decision making process" (Morecroft 1982,p.24).

Morecroft (1992) presented two unique knowledge representation structures designed to help management teams construct System Dynamics models. "The value chain provides a working - space of boxes and labels to categorize facts. The mapping symbols provide building blocks to assemble and connect knowledge about the operating policies of a business" Morecroft (1992, p.13)

The second knowledge structure Morecroft (1992) presented was the policy function, where a set of filters is associated with decision making. "Each filter has a label to signify what process of the organization is conditioning information flow - operating goals, measurement systems, organizational structure, or culture and tradition" (Morecroft 1992, p.12). Each information link is associated with one of these filters. Policy functions can be discussed indepth, one at a time, or linked together (like a policy structure diagram) to provide a broad mapping of operating structure.

Different names and approaches are associated with 'flow diagrams'. Sometimes referred to as DYNAMO flow diagrams, STELLA diagrams, Forrester diagrams, or Stock & flow diagrams, they are the knowledge representation structure most central to the System Dynamics methodology. While more complex than causal loop diagrams and more detailed than policy structure diagrams, structurally, they most closely reflect the model to be formulated and simulated.

Constants are the simplest knowledge representation structure, but their selection is very critical to determining model behavior. Model constants help to establish the temporal boundaries, and spatial boundaries. Little has been written concerning the selection of the model time frame. Generally model delay times are either constant or functions with a time constant as a parameter. The time interval between data points is another vital time constant. Weekly data points may generate a quite differently shaped curve than monthly data points. Constants may be established to simplify the model and help bring it to closure. The process of how and when to establish constants is an area in itself worth investigation, given the implications concerning knowledge elicitation and boundary establishment.

A widely used form of expressing knowledge, which has not been discussed is 'prose'. For example, a written statement defining the modelling purpose or perspective represents knowledge. This is generally not considered a 'structure', unless certain constraints are placed on the form of the statement or its contents. The "Dynamic Hypotheses" is a prose description of system structure, performance and pattern causality that is referred to often in the System Dynamics literature. Logic statements, exogenous "data" inputs, and deterministic and statistical equations are not covered since they are usually first encountered (after model conceptualization) during model formulation. Knowledge representation structures determined by system participants are used in various studies. Because they developed from the experiential base of the system participants, they tend to be a better reflection of their mental models.

Rules have been the dominant structure for conveying knowledge in expert systems. A rule is a conditional statement: **IF {*a given condition exist*} THEN {*initiate a particular action, or draw a particular conclusion*}**. Rules are linked together, such that certain rules draw conclusions that then establish the conditions for other rules. A set of rules can effectively convey a single expert's decisionmaking process, or a policy implemented in a collective process. Complex IF_THEN_ELSE conditions can be used to account for all the options covered by a policy. An example of a policy rule is: **IF {*deposits* > $20,000} THEN {*interest = 5% of deposits*} ELSE IF{*deposits* > $2,000} THEN {*interest = 4% of deposits*} ELSE {*interest = 3% of deposits*}.**

Tables, one of the most popular knowledge structures, vary in complexity from a simple single column table, to large multidimensional structures. Any information that lends itself to being detailed as a list, and then elaborated on can be displayed using tables. For example, a table can be used to list system resources, their different states and initial values. While tables are structures of two or more dimensions where the cells have unique values, grids are multidimensional structures where unique elements or characteristics are listed along the axis and the values in the cells are relational (rating, rankings, or logical indicators). The repertory grid discussed above is an example.

Scenarios are one type of knowledge structure that allows the analyst to relay the temporal and causal reality of a process or situation. However, some scenarios only relay the temporal dimension. Scenarios are a ordered list of statements about a system that convey information on the state of the system at different points in time. A statement in this ordered list may relate a condition, an action, or both. Scenarios may be used to document the history of a system or present future potentialities. Scenarios may be provided by a system analyst as a basis for eliciting information from respondents, or the analyst may request the respondent to provide scenarios.

McGraw and Harbison-Briggs (1989, p.21-24) categorized knowledge into four groups: procedural, declarative, semantic, and episodic. 'Procedural knowledge' includes the skills an individual knows how to perform. This type of knowledge involves an automatic response to stimuli and may be reactionary in nature. 'Declarative knowledge' represents surface level information that can be verbalized. It is what one is aware of knowing. 'Semantic knowledge' represents one of the two theoretical types of long term memory. It reflects cognitive structure, organization, and representation. 'Episodic knowledge' is experiential information that one has grouped or chunked by episodes. It is temporal and spatial in nature. Different types of elicitation techniques are associated with each type of knowledge. Different System Dynamics activities reflect different types of knowledge, and require different knowledge structures. Exhibit 1 gives possible matching of knowledge type, System Dynamics activity, knowledge structure, and elicitation technique.

Exhibit 1: Knowledge Acquisition Table

Knowledge	Activity	Structures	Techniques
Declarative Knowledge	Identify purpose, perspective, problems, and time horizon	checklists, forms, variables, constants, graphs, prose	brainstorming, interviews, surveys, committees
Semantic Knowledge	Identify policymakers, resources, and their states, and subsystems	Grids, tables, lists, subsystem diagram	job analysis, repertory grids, structured interviews
Procedural Knowledge	Identify decision making procedures,	Policy rules, Policy functions	task analysis, process tracing
Episodic Knowledge	conceptualization of flows	Scenarios, Flow diagrams	process tracing, protocol analysis, interviews

APPROACHES USED TO ELICIT INFO FROM SYSTEM DYNAMICS ANALYSTS

Group Process

The elicitation of knowledge in a group setting allowed the collective development of ideas, and feedback. It also allowed the presentation of information on knowledge acquisition techniques and structures used in other fields, and the facilitation of discussion on how they could be used in System Dynamics. The group sessions were conducted with 5 local System Dynamics practitioners, all had done some modelling using System Dynamics, but only one had published in the the field. First, information was presented regarding knowledge acquisition techniques and structures that could possibly be borrowed from expert systems development, this was followed by discussion, and then a modified version of the Nominal Group Technique was conducted. This process required two 2 hour sessions and individual end interviews. The steps in the Modified NGT process are listed below:

Step 1: Silent Idea Generation . Each participant, writes down System Dynamics activities believed to be central to problem formulation and model conceptualization. A System Dynamics activity is described by indicating who is involved, and the knowledge acquisition methods and structures used. The activity lists are given to the group facilitator.

Step 2:Group Round-Robin listing of Activities: Sequentially, without explanation or comment from the group, the facilitator writes all of the System Dynamics activities on the Board for everyone to see. Each knowledge acquisition technique and knowledge structure is clearly indicated.

Step 3: Discussion and Clarification of Listed Activities Each activity is discussed informally by the group to gain clarity. Activities may be added, deleted or combined during the discussion.

Step 4: Individual Written Ratings of Activities: Participants silently and independently rate each activity based on the effectiveness of its knowledge acquisition techniques and knowledge structures.

Step 5: Discussion of Ratings with Group facilitator: The group facilitator meets individually with each group member. They discuss the ratings and comments made in step 4.

Step 6: Final Written Rating: Each participant silently and independently rates each activity

Twelve activities were generated. All participants indicated, given more time, they would have listed more activities. Of the 12, 9 activities included knowledge acquisition techniques other than the non specific interview. There was no consensus with the first ratings, and no significant convergence with the second ratings. On a scale of 1 to 10 (10 means ideal way to conduct activity), 8 activities received ratings of at least 8, and 5 were rated 9 or above. Of the 6 activities rated higher than 8.7, protocol analysis was used in 3 and process tracing 2. Knowledge structures suggested included simple variables, time histories, scenarios, rules, tables, grids, and causal loops. The group felt the exercise was insightful regarding knowledge acquisition and knowledge representation. They also concluded that problem formulation and model conceptualization activities are partially context and domain dependent.

Interviews

Interviews were the most direct method of eliciting information. The personal contact, and undivided attention had advantages over group sessions, and contact through mail. Time and availability constraints limited the number of experienced System Dynamics analysts that could be interviewed to three. The three analysts interviewed averaged 22 years of experience in System Dynamics, had published papers on System Dynamics and taught courses involving System Dynamics. The questions were distributed in advance and a semi structured interview was conducted. In addition to the questions, each interviewee was given a short document outlining the research. For the initial interview, the time spent ranged from one session of one hour to three sessions totally seven hours. Five multiple part questions were asked. Two were dealing with knowledge elicitation and knowledge representation structures, and one question requested information regarding the respondent's involvement with System Dynamics. The other two questions dealt with the preparation needed to conduct System Dynamics studies, and will be addressed in a separate paper. A second set of interviews was conducted, asking four questions concerning a knowledge acquisition process presented. These interviews were each one session ranging from one to two hours. Only two of the experts were available for the second set of interviews. The main hypotheses for the interviews were:
1) Experts will provide information distinctly different from each other, and some experts will be unaware of significant work done regarding knowledge acquisition in System Dynamics.
2) Experts will provide more indepth information than the group session.
3) Due to time demands on some experts, all questions may not be completely covered.
4) Respondents will give favorable responses to the knowledge acquisition process presented, but will be reluctant to employ it, until it has been used in one or more studies, and the results presented for evaluation by other System Dynamics analysts.

While all three respondents used interviews as an elicitation technique, the structuring of the interviews ranged from very informal to semi structured. The first analyst also relied on interactive modeling and detailed questionnaires, the third also depended heavily on observation, sitting in on meetings and being involved in the organization, and all three included literature review as a knowledge source. The first analyst depends primarily on causal diagrams and flow diagrams. His position was "if System Dynamics stopped with a causal model, in most cases it would be fine". The second analyst felt the most useful knowledge representation structures were time histories. He felt after generating and/or simulating time histories, they should be linked to causal loops. The third analyst relied heavily on time histories, but felt the most important knowledge representation was verbal, the use of words in communicating with the client and other system participants. The third analyst also felt the use of knowledge representation structures varies with the background of the client, and that an analyst should select structures after they become familiar with the study participants. Both experts, interviewed the second time, were supportive of using the suggested approach to problem formulation and model conceptualization. They felt its use should be pursued. They suggested adding observation as an elicitation approach and considering what preliminary study is needed by the System Dynamics analysts to become familiar with the domain. The former was added to the approach. The latter will be handled at a different time. The modified approach appears below in Exhibit 2. It draws on inputs from the Delphi process, and the group process, as well as the interviews.

Delphi

The use of the Delphi technique allowed knowledge elicitation from a representative number of System Dynamics experts from a diversity of locations. The multiple questionnaire nature of the Delphi, allowed feedback among the experts. Since the Delphi is currently still in the second round, this paper only deals with results from the pre-Delphi questionnaire and the first round. The hypotheses included all of the hypotheses stated above for interviews, in addition to the following:
1) Slow response by some respondents will slow down the Delphi process, 2) Due to experts' busy schedules there will be a fairly high participant dropout, and 3) Due to uneven concern over

knowledge acquisition, and this Delphi, some responses will be very detailed, and others brief. To minimize participant dropout, a letter and pre-Delphi questionnaire were sent to 49 System Dynamics analysts, explaining the purpose and process of the Delphi.

Of the 49 analyst sent pre-Delphi questionnaires, 34 responded, 30 agreed to participant, and 21 responded to the first round. The average rating of the level of importance placed on developing knowledge acquisition techniques and structures in System Dynamics was 4.3, on a scale of 1 to 5 (5=very important). Twelve different elicitation techniques were suggested for problem formulation and fourteen for conceptualization. They included structured interview, brainstorming, issuing questionnaires, interpretive structural modeling, Delphi, and interactive model developing in group sessions. Most analysts combined more than one elicitation technique in their suggested approach. The respondents suggested 23 distinctly different knowledge representation structures for problem formulation and 21 different structures for model conceptualization. Many of the same structures were suggested for both phases. In addition to the System Dynamics knowledge structures mentioned earlier in this paper, a sample of the structures used by analysts include: prototype model output, list of critical management issues, environmental scenarios, Axelrod's cognitive map, Bullet chart, hexagon diagrams, and table functions. As expected, some responses were quite detailed, while others were extremely brief.

A PROBLEM FORMULATION AND MODEL CONCEPTUALIZATION PROCESS

Problem formulation begins with an unstructured interview with the client, or an informal brainstorming session involving key members of the analysis team and key system participants. A preliminary problem definition is sketched during this activity.

Collecting and analyzing organizational data, and eliciting the interpretation of this data by system participants is important in problem formulation. The System Dynamics analysts may use protocol analysis to restructure some of this information, and present the restructured information to the system participants for evaluation. Whenever possible, the analysts should use observation as a source of knowledge.

A series of interviews going from unstructured to semi structured are used to: formulate a concise study purpose, list the resources relevant to the problem and identify their different states (from this a 'resource-state table' is constructed), and develop the initial dynamic hypotheses with supporting graphs representing the reference mode. The agenda of each interview is determined by the results of preceding interviews.

Task analysis is used to identify the policies and generate a policy - policymakers grid, which indicates which system participants influence each policy.

Starting with the initial dynamic hypothesis and resource/state table, develop a flow diagram without information links.

Have participants identified through the policies and policymakers grid evaluate the flow diagram and clarify the policies by developing policy rules. Have the participants use process tracing to generate scenarios based on their involvement with policies. These scenarios and policy rules are used by the System Dynamics analysts or in a group session with system participants to add information links to the flow diagram. Review the flow diagram with participants. This is an iterative process requiring additional scenarios and revisions to the policy rules and flow diagram.

Exhibit 2: The "Modified Approach" to Problem Formulation and Model Conceptualization

CONCLUSIONS

System Dynamics analysts uneven awareness of knowledge acquisition developments in System Dynamics and other fields, coupled with their interest in further developing knowledge acquisition techniques and structures (a high interest was displayed in the group sessions), led to the conclusion that knowledge acquisition skills should be more explicitly included in System Dynamics training and more consciously used in practice. An extension of the group process used in this research would be useful to include in the System Dynamics curriculum.

The diversity in responses, and the position expressed in all three processes that knowledge acquisition is context and domain dependent, led to the conclusion that there is no ideal approach to knowledge acquisition. The data collected, particularly through interviews and the Delphi process, would be useful in developing an expert system to select knowledge acquisition techniques and structures based on the context and domain of the situation. This would be a helpful training tool for students, and a decision support system for novices in System Dynamics studies. A group process with Delphi participants should be used to collectively clarify what analysts feel should be done to enhance knowledge acquisition in System Dynamics.

It appeared the positions of the different analysts interviewed directly reflected their stated view of System Dynamics. One analyst felt System Dynamics is an important tool that must find its proper place in science. This position is reflected in his tendency to draw on techniques widely used in other areas such as interactive modelling and the use of questionnaires, and his belief that "in most cases it would be fine to stop the System Dynamics process once a causal diagram is developed." Another analyst felt System Dynamics is the central organizing principle of life, and placed a heavy emphasis on observation, verbal communication, and the need for the analyst conducting a study to be a key decisionmaker in the system. To establish a strong correlation between analysts' views of System Dynamics, and their approach to knowledge acquisition, more analysts must be interviewed.

The reaction to new techniques and structures indicate it is worth pursuing their use in actual System Dynamics studies to determine under what conditions the new techniques and structures are useful. Preliminary indications are that group process techniques are more effective, and that knowledge structures using the participants' terminology are preferred.

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