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Abstract

Knowledge intensive processes are often driven and constrained by the mental models of experts acting as direct participants or managers. For example, product development is guided by expert knowledge including critical process relationships which are dynamic, biased by individual perspectives and goals, conditioned by experience, aggregate many system components and relationships and are often nonlinear. Descriptions of these relationships are not generally available from traditional data sources such as company records but are stored in the mental models of the process experts. Often the knowledge is not explicit but tacit, so it is difficult to describe, examine and use. Consequently, improvement of complex processes is plagued by false starts, failures, institutional and interpersonal conflict, and policy resistance. Formal modeling approaches such as system dynamics are often used to help improve system performance. However, modelers face great difficulties in eliciting and representing the knowledge of the experts in these systems so useful models can be developed. Increased clarity and specificity are required concerning the methods used to elicit expert knowledge for modeling. We propose, describe and illustrate an elicitation method which uses formal modeling and three description format transformations to help experts explicate their tacit knowledge. To illustrate the approach we describe the use of the method to elicit detailed process knowledge describing the development of a new semiconductor chip. The method improved model accuracy and credibility in the eyes of the participants and provided tools for development team mental model improvement. We evaluate our method to identify future research opportunities.

Introduction

Many public and private sector systems increasingly depend on knowledge intensive processes managed and operated by interdisciplinary teams. These systems are difficult to manage. Often formal models such as system dynamics models are used to help managers understand the sources of difficulties and design more effective policies. Typically, the expert knowledge of the people who actually operate the system is required to structure and parameterize a useful model. To develop a useful model which is also credible in the eyes of the managers, however, modelers must elicit from these experts information about system structure and governing policies, and then use this information to develop the model. While many methods to elicit information from experts have been developed, most assist in the early phases of modeling: problem articulation, boundary selection, identification of variables, and qualitative causal mapping. These methods are often used in conceptual modeling, that is, in modeling efforts which stop short of the development of a formal model which can be used to test hypotheses and proposed policies. The literature is comparatively silent, however, regarding methods to elicit the information required to estimate the parameters, initial conditions, and behavioral relationships which must be specified precisely in formal modeling.

Much of the information about system structure and decision processes resides in the mental models of process participants, where it remains tacit (Nonaka and Takeuchi, 1995; Forrester, 1994; Polanyi, 1966). Compared to explicit knowledge, tacit knowledge is subjective, personal, and context-specific. It is difficult to describe, examine and use. Therefore an important activity in modeling these systems is the elicitation, articulation and description of knowledge held in the mental models of system experts. By system expert we mean those people who participate in the process directly in operational or managerial roles. We seek to improve modeling and mental model improvement techniques by proposing and testing a method of expert knowledge elicitation. The method we develop is designed to assist modelers and their clients specify parameters and relationships in a form suitable for formal modeling. We also argue, however, that the additional precision and discipline required to elicit information about these relationships in a form suitable for formal modeling can yield insights of value to modelers and clients even when no formal model is contemplated or built.

We illustrate the use of the technique with an example drawn from a model of the development of a high-tech product. Product development is one of many processes in which globalization, accelerated technology evolution and increased customer sophistication have resulted in a dramatic increase in complexity and a corresponding rise in cost overruns, delays, quality problems and outright failures. Under pressure to bring new products to market ever faster and cheaper, methods such as concurrent development and co-located cross functional teams have been widely adopted. Concurrent product development requires multiple knowledge-driven processes such as design which produces descriptions of the final product and quality assurance which transforms unchecked designs into approved designs or designs requiring changes. Effective product development and effective modeling of product development depend on knowledge of these critical process relationships which are dynamic, nonlinear, biased by individual perspectives and goals, conditioned by experience, and aggregate many system components and relationships. Descriptions of process relationships are often not generally available from traditional data sources such as company records but are stored in the mental models of the process experts. Differences in the mental models of team members can constrain progress and lead to conflict. The frequently divergent mental models of marketing managers and design engineers regarding the sequence of steps required to develop a product concept into a detailed design provide examples (Ford and Sterman 1997, Clark and Fujimoto 1990, Kim 1993). System dynamics models of these systems must include the process knowledge of system experts which drive and constrain these processes (Barlas 1996, Williams, Eden, Ackermann and Tait 1995, Wolstenholme 1994; Richardson and Pugh 1981, Lyneis 1980, Forrester and Senge 1980). The complexity of modern product development processes provides a rich setting in which to test our method for eliciting the information required to specify and parameterize formal simulation models.

Methods of Expert Knowledge Elicitation for Modeling

Most system dynamics research on knowledge elicitation for model building has focused on the identification of system components and causal links to formulate conceptual models (e.g. Vennix and Gubbels 1994). Vennix, Anderson, Richardson and Rohrbaugh (1994) review the knowledge elicitation literature for group decision support. They find that elicitation techniques are generally used for problem definition, model conceptualization and model boundary definition. They mention a role for information elicitation in model formulation but do not describe a method for doing so. They identify five factors which should guide knowledge elicitation methods: (1) the purpose of the modeling effort; (2) the phase of the model-building process and type of task being performed (e.g. elicitation, exploration or evaluation); (3) the number of people involved in the elicitation process; (4) the time available and (5) the cost of the elicitation methods.

Morecroft and van der Heijden (1994) describe in detail the method used to elicit expert knowledge for conceptual model development (phase 1 of Morecroft's (1985) two phase modeling approach). However formal modeling and the description of tacit expert process knowledge with the detail and precision required to improve complex, tacit mental models requires the description of relations at an operational level, i.e. at a level which describes the specific characteristics which relate individual system elements. Formal modeling requires more precision than purely conceptual modeling. Formal modeling requires specification of stock and flow structure, functional forms, and numerical estimates of parameters and behavioral relationships. Such knowledge goes well beyond the types of data typically elicited from participants in the early stages of modeling or in purely conceptual modeling studies. Morecroft and van der Heijden describe the use of expert knowledge for specifying relationships (part of Morecroft's second modeling phase) only briefly. In fact Morecroft and van der Heijden consider this use of expert knowledge to be unusually difficult. They lament "It is difficult to imagine how one would have engaged the full team [of 10 experts] in this more detailed work."

Methods of expert knowledge elicitation for parameter estimation have been mentioned (e.g. by Graham, 1980) but not extensively addressed in the literature. While the knowledge elicitation literature is comparatively silent regarding methods to estimate functions and parametric relationships, standard system dynamics methodology includes a number of methods designed to help the modeler or student estimate these relationships. For example, techniques to estimate nonlinear relations between variables ("table" or "graph" functions) include identifying reference points (points where the relationship takes on a specified value by definition or based on high confidence), reference curves defining a particular policy or behavior, and extreme conditions tests (see e.g. Richardson and Pugh, 1981). However, much of the skill involved in estimating nonlinear relationships by expert modelers also remains tacit, passed on from teacher to student in apprenticeships. While expert system dynamics modelers no doubt use these skills in their fieldwork, there is essentially no published literature describing their use in field settings and no literature evaluating their effectiveness.

Methods for eliciting expert knowledge in product development contexts have been addressed by several authors. The objective of most methods has been the development of conceptual designs and models. For example Nonaka and Takeuchi (1995) combine the elicitation of tacit knowledge and its transformation into explicit knowledge with three other knowledge conversions to generate organizational knowledge for developing product concepts. They propose three steps to make tacit knowledge explicit: describe system knowledge with metaphors, integrate metaphors with analogies and model the resulting product concepts. They provide evidence for the effectiveness of the first two steps in Japanese self-organizing development teams. However Nonaka and Takeuchi use modeling only to develop "rough descriptions or drawings, far from being fully specific" (p. 67). While effective in a concept development context, the metaphor-analogy-model method produces knowledge descriptions which are not explicit or specific enough to be used in formal models. Similarly, Burchill and Fine (1997) describe a qualitative method for concept generation and also discuss the use of causal loop diagrams to map the feedbacks involved in concept development for new products. Their method, while carefully grounded in coding of participant comments, yields causal loop diagrams capturing participant beliefs about the processes governing time to market but none of the quantitative information needed to specify and test these hypotheses.

More clarity and precision are required in knowledge elicitation for specifying, validating and analyzing formal model relationships and parameters than for conceptual modeling. Elicitation methods which are effective for conceptual modeling are necessary but far from sufficient. We seek to understand how modelers and system experts can elicit specific structural system knowledge for formal modeling and mental model improvement. We also argue that these techniques generate valuable information even when no formal model is contemplated.

Our method is motivated by the diversity of characteristics of information sources for modeling. Forrester (1994) categorizes knowledge sources for system dynamics modeling as mental, written or numerical and analyzes the strengths and weaknesses of each form. Mental models are expansive in scope and richness of available information. Written knowledge descriptions have the advantages of being codified and therefore more widely accessible than mental model knowledge; written descriptions facilitate the abstraction of more detailed mental model data. But written knowledge is limited by: (1) the richness it can describe, (2) the inability of modelers to query written knowledge to test, expand and understand it beyond the text and (3) being filtered and biased during codification. Forrester considers numerical data to be the narrowest of the three knowledge forms in scope and lacking in supporting contextual information about the structure which generated the numerical data. However numerical data are critical for estimating specific parameters for modeling, establishing patterns of behavior and for some forms of model testing (Homer, 1996; Sterman, 1984; Forrester and Senge, 1980). Forrester clearly sees value in all three knowledge description forms for modeling, and argues against the bias of some schools of modeling against use of the mental and written databases. However, Forrester does not address how modelers can access the benefits of all three knowledge types while avoiding their weaknesses.

Our method aids in knowledge description by focusing the development of a formal model as the eventual product of the effort. We hypothesize that pushing experts to describe relationships at the simulation model level helps them to clarify and specify their knowledge more than they would if we worked at a more abstract level using tools such as causal loop diagrams. We believe this is true even if no formal model is ever built, though of course the process of formal modeling almost always yields additional insight into problem situations (see e.g. Forrester 1961; Sterman, 1994; Homer, 1996). Our method also differs from knowledge elicitation approaches which seek a shared image from a group of experts and which abstract expert knowledge for the purpose of reaching consensus. Later we will describe how our method utilizes differences among individual expert descriptions to improve formal modeling and mental models.

The Knowledge Elicitation Method

Our method structures the development of knowledge descriptions into three sequential phases: the positioning, description and discussion phases:

The Positioning Phase

The purpose of the positioning phase is to establish a context and goals for the description process. The positioning phase has three steps:

1. Establish context: The facilitator creates an environment in which the elicitation will occur by briefly describing the model purpose, major subsystems and their interactions, the roles and structures of the subsystem and the relationship to be characterized. The context provides experts with a reason for developing the descriptions, bounds on the scope of the model, an initial focus of attention and a transition period from their activities prior to the elicitation workshop. Context setting prepares the experts for the description work ahead in the same sense that Morecroft and van der Heijden (1994) "conditioned" a group of oil industry experts as a prelude to knowledge elicitation for model building. Usually there will have been prior modeling work including problem articulation, boundary selection, and even the development of initial working simulations. Of course such initial models, boundaries, and even the basic definition of the problematic issue to be modeled are always provisional and may change as the modeling process iterates; indeed detecting inadequacies in problem definition, model boundary, and formulations is the main purpose of our method and of iteration in modeling in general (Forrester 1971/1985, Sterman 1994, Homer 1996).

2. Focus on one relationship at a time: Two activities narrow the experts' attention to a single relationship. First the facilitator describes the relationship operationally by identifying and defining the input and output variables which the relationship describes with units of measure, where the relationship is used in the model, why the relationship is important and what other parts of the system and model the relationship affects. This activity assures that the experts understand exactly what part of the system is to be described. Second, the facilitator provides a description aid which helps experts make explicit and codify their knowledge. One example of such aids is a "graphic frame" which can be used to describe a (possibly nonlinear) relationship between two variables (see below).

3. Illustrate the method: Each expert is given a set of relationship description worksheets which have been completed based on an example from an analogous setting. The facilitator explains the examples in detail, using the four steps of the description phase to illustrate the process and reasoning the experts will use to describe the relationship in their own system.

The Description Phase

The description phase guides experts through the sequential development of four different descriptions of the relationship. Each description takes a different form and serves a unique purpose in the process of transforming their tacit knowledge into usable form. During the description phase the experts are directed to use their own images and not to interact with the other experts.

4. Visual description: Experts are first asked to visualize the process, to "see a picture in your mind of what happens". In the case of a product development process, the experts imagine (presumably in pictures) the flow of the work described by the relationship. Experts are invited to close their eyes or otherwise disengage from others during this step. The purpose of this step is to *activate, bound* and *clarify* the experts' mental images of the relationship.

5. Verbal description: Experts are then asked to "tell the story of what happens" to themselves. Experts are encouraged to use a large unstructured portion of the description worksheet to write informal notes about their mental image. The informal and solely individual use of these notes is emphasized to encourage their use. The purpose of the verbal description is to transform the expert's mental image of the process and relationship into a more explicit form and begin to codify their knowledge. The completeness or accuracy of descriptions is not emphasized until the discussion phase of the method.

6. Textual description: Experts are then directed to capture their 'story' in writing on the worksheets. The textual description generates a more specific codified description of the expert's knowledge by constraining the feasible shape of the relationship. In particular, for the specification of a nonlinear relationship between variables, the experts are directed to identify anchor points and the reasoning or data justifying them. Anchor points are those values of the relationship required by system constraints (e.g. shipments must fall to zero when inventory is zero), defined by convention (e.g. the 1997 value = 1.0) or in which the expert has high confidence. A separate portion of the description worksheet provides spaces for anchor point coordinates and the basis for each point, and the definition of anchor points is reiterated from the examples explained in step 3 (Illustrate the method) to assist the experts.

7. Graphic description: Experts then create a graphic description of the relationship in two steps. First the anchor points are plotted on an empty graphic frame provided on the description worksheet. Then experts consider the shape of the relationship between anchor points and use that reasoning to draw their estimate of the relationship. The facilitator emphasizes that the second step is significantly more than connecting the anchor points with straight lines and illustrates the use of nonlinear relationships to describe a relationship. The experts are not directed to generate smooth graphs. The objective of the method is to elicit and describe expert knowledge as accurately as possible and not as constrained by expectations about relationship continuity. However, the experts are directed to explain and provide justification and data for any inflections and discontinuities in terms of the underlying process.

The Discussion Phase

The discussion phase seeks to test, understand and improve the descriptions of different experts. We base this phase on the estimate-feedback-talk protocol suggested by Vennix and Gubbels (1994) because of its focus on the assumptions underlying tacit knowledge and adapt the protocol to our focus on describing and understanding rather than consensus-building. The discussion phase begins by displaying the graphic frames containing the descriptions generated by the different experts side by side.

8. Examine individual descriptions: Each expert shares their verbal description with the group as a basis for explaining the anchor points and shape of their graphic description. This step provides an internal test of description consistency by comparing multiple descriptions of a single relationship developed by a single expert. The verbal and graphic descriptions can provide enlightening information concerning the expert's visual description. Anchor points prove valuable as checks against the limits of relationships and as the basis for the reasoning behind individual estimates. The underlying mental model leading to a critical activity or anchor point may become clear only through the description of the shapes assigned to the areas between anchor points.

9. Compare descriptions: Differences among descriptions are inevitable because of the complexity of the relationships being described and the incomplete and particular knowledge of different experts. These differences naturally lead the experts to discuss their mental models and assumptions used to describe the relationship. The facilitator directs the experts to identify and investigate the causes of differences based on their roles in the process, relationships among functional groups and organizational structures. No attempt is made to resolve differences or reach consensus. This step provides an external test of individual descriptions by comparing them with those of other experts with different roles and perspectives.

The elicitation process uses a focus on formal modeling and a single specific relationship to prepare experts to transform their tacit knowledge into usable forms. Individual experts develop multiple descriptions of the same knowledge in different formats. The descriptions are tested through their use by individuals to communicate with other experts and by comparison of individual descriptions among colleagues. The method provides several advantages over interview-based or group modeling approaches to knowledge elicitation: (1) information losses during elicitation are reduced compared to single-step processes through the use of several small, separate and explicit format transitions; (2) the generation of multiple descriptions in different formats by a single expert allows testing and improvement through triangulation; (3) the generation of multiple individually-generated descriptions in a group context allows testing and improvement of descriptions through comparison to the views of other experts while reducing the potential for group-think and premature convergence.

Example: Eliciting Knowledge of Product Development Processes

We used our knowledge elicitation method to model process relationships in a product development project (called "Python" here) which created a moderately complex ASIC (application specific integrated circuit) for a major player in the semiconductor industry. The process was used to develop two types of concurrence relationships which relate the amount of work completed to the amount of work which is available to be completed (Ford and Sterman, 1997). Complex development projects consist of multiple phases such as design, prototyping, and testing. The ability of the engineers responsible for an activity to begin and successfully complete their work depends on the timing and quality of the work released to them by other activities. For example, prototype builds cannot begin until at least some design information (usually engineering drawings and associated technical specifications) are completed and released. Sometimes an activity can begin its work with partial and incomplete information; in other cases all upstream work must be completed before a downstream activity can begin. In project and product development models *concurrence relationships* describe the constraint imposed on one activity by another. Concurrence relations describe the degree to which activities can be carried out in parallel or must be done sequentially. *External concurrence relationships* describe the dependency of the development tasks in a downstream phase on the release of tasks from an upstream phase, such as the constraint imposed on testing by the release of design work. *Internal concurrence relationships* describe the inter-dependency of the development tasks within a single development phase. Internal concurrence relationships are necessary because each phase in a development project aggregates a number of different activities. Not all the activities in a given phase can always be done independently. For example, consider the construction phase of a building. The second floor cannot be built until the structural members for the first are completed. This sequentiality is captured by the internal concurrence relationship (see below for a detailed example).

Seven concurrence relationships were developed based on twenty three expert estimates from developers and managers of the Python project. The parameter estimates were developed in a set of seven workshops averaging forty-five minutes in duration. Each workshop developed a single concurrence relationship with a different set of experts. Developers and managers responsible for each project phase participated in the workshop to develop the internal concurrence relationship for their phase. The workshops to develop the external concurrence relationships included those responsible for the relevant upstream and downstream phases.

Developers and managers of the Python project were invited to participate in the workshops. Experts had an average of over ten years of experience working in the development of computer chips and a minimum of five years experience in the company's product development organization. Most developers in the Python organization also have management roles in development projects, often making the distinction between developers and managers unclear and sometimes meaningless. The experts were familiar with the system dynamics approach to modeling product development projects (Ford, 1995) and several had received training in systems thinking (Voyer, Gould and Ford, 1996). A few of the experts had heard an informal conceptual description of the model but none had knowledge of the formal model structure or descriptions of specific relationships used in the formal model. The number of participants in each workshop varied from two to five, depending primarily on the number of personnel in each development phase and whether the concurrence relationship to be estimated was internal or external. No experts left during the workshops. One participant in one workshop was initially unable to describe a relationship. How this was addressed is described below.

The Positioning Phase

1. Establish context: The facilitator described the model purpose as the modeling of development processes within a single development project to improve the understanding of how those processes affect product development performance. A diagram facilitated the description of the general model structure as a linked set of development phase modules (Figure 1). This helped the experts focus on the four phases used in the model: product definition, design, test prototype and reliability/quality control.

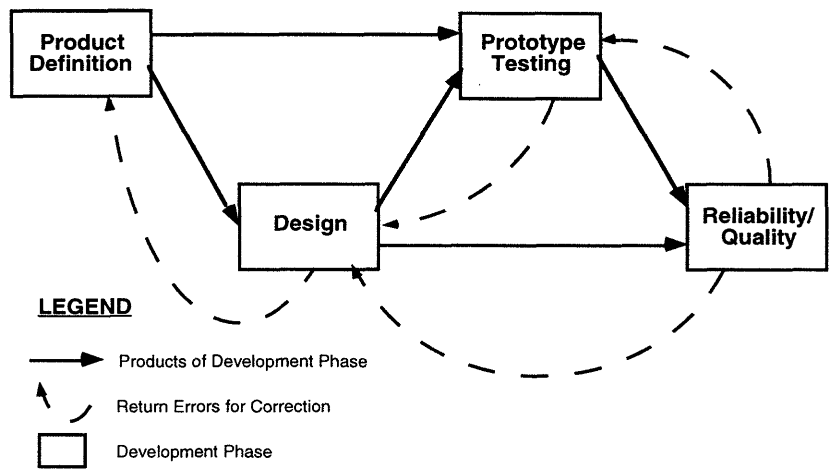

Figure 1. Model Structure as a Network of linked Development Phases used in the Positioning Phase

The description of each phase as a generic structure which is customized to reflect specific stages of product development included an overview of the four subsystems which interact to drive project performance (Figure 2). Development processes describe the movement and accumulation of development work based on four activities in each phase: initial completion, quality assurance, iteration and coordination. Resources are allocated to activities based upon the relative pressures for each activity as perceived by developers and management. The Scope subsystem defines phase sizes and relative need for changes in work. The Targets subsystem describes project objectives and performance with the three traditional measures (time, quality and cost). Primary subsystem interactions include floating goal structures, resource constraints and the generation of a demand for resources by development processes. Ford and Sterman (1997) and Ford (1995) provide more detailed descriptions of the model. The development process portion of the model was identified as the focus of the description effort. The facilitator explained the importance of including the experts' knowledge in the model and the tacit nature of that knowledge as the reason for using description workshops to gather data beyond previous interviews involving most of the workshop participants.

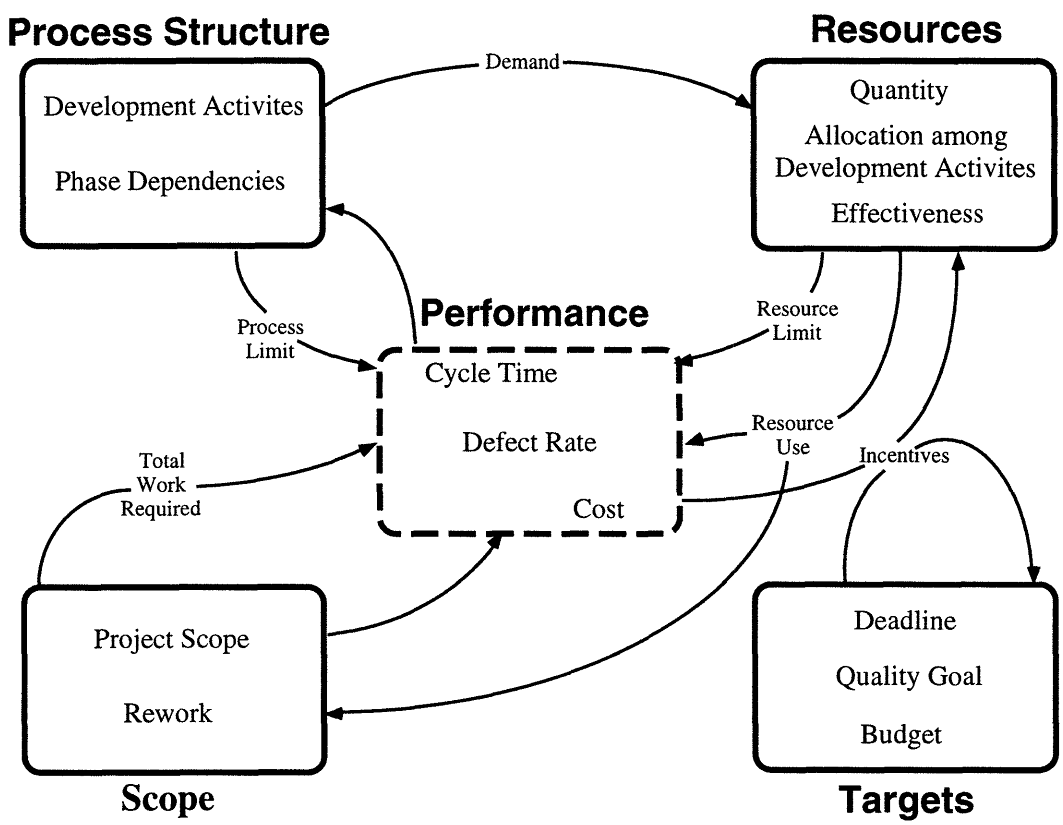

Figure 2. Model Subsystems in a Single Development Phase used in the Positioning Phase

2. Focus on one relationship at a time: The facilitator first described and defined internal and external concurrence relationships. External concurrence relationships were operationalized by defining the independent variable as the fraction of the development tasks in the scope of an upstream phase which has been released to the downstream phase. The dependent variable is the fraction of development tasks in the scope of the downstream phase which can be completed. Both parameters have a range of 0 - 100% of the phase scope (the number of tasks to be completed). For internal concurrence relationships the independent variable is the percent of the development tasks for the phase which are perceived by the developers to be completed correctly. The dependent variable is the percent of development tasks in the same phase which can be completed. Both parameters have a range of 0 - 100% of the phase scope. The role of these relationships in constraining project progress independently and interactively with project resources was described.

To facilitate the description of concurrence relationships by the experts the facilitator provided a "graphic frame" for each type of concurrence relationship. Figure 3 shows a graphic frame for an external concurrence relationship. The frame is a box in which the abscissa represents the independent variable and the ordinate represents the dependent variable using the definitions above. The facilitator described the variables and the range and scales of the axes.

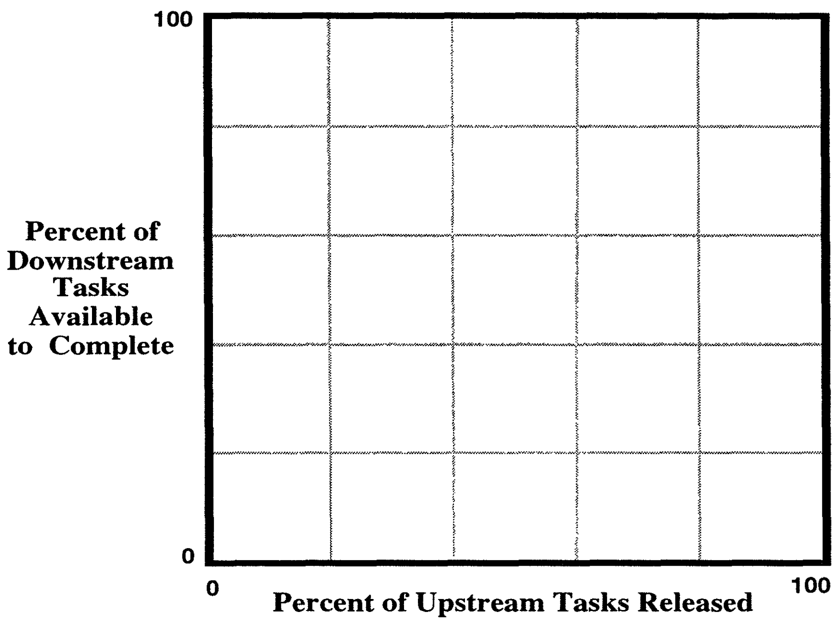

Figure 3: A Graphic Frame for Describing External Concurrence Relationships

3. Illustrate the method: To illustrate the description method simple examples in a different but familiar domain were described. The construction of the steel skeleton for an office building was used as the illustrative example. Examples of three internal and two external concurrence relationships in the structural steel example were used to illustrate the process and demonstrate the variety of possible relationships which can be described. Multiple examples were provided to reduce suggestion bias. Paper copies of the examples were provided to experts as a convenient and useful reference.

As an example consider the internal concurrence relationship for the Erect Steel phase. Not all tasks involved in erecting the steel skeleton for an office tower can be accomplished simultaneously.

The internal concurrence relationship for this phase of the construction project captures the physical constraint that the building must be erected sequentially one floor at a time from the ground up because lower floors support those above. The work of placing the beams and girders for the next floor cannot be done until the members for the previous floor have been placed and secured. The completion of one floor makes another floor of work available. In a ten story building, completing the first 10% of the work (one floor) makes it feasible for the crew to do the next 10% (the second floor), and so on. Anchor points were identified as shown in Table 1 to transform this verbal description into a more precise form.

Percent of Tasks Perceived Satisfactory	Percent of Tasks Completed or Available to Complete	Notes
0	10	Can do 1st floor at start
10	20	Completing first floor makes 2nd floor available
20	30	same
...	...	...
90	100	Completing 9th floor makes entire structure available
100	100	Building structure erection complete

Table 1: 'Erect Steel' Example of Internal Concurrence Relationship Anchor Points

Figure 4 shows the graphic description of the internal concurrence relationship for the Erect Steel phase of the office building example. The linear progression reflects the sequential increase in the number of total floors available for steel erection as work proceeds up the building.

The developers and managers found the construction example easy to understand despite the differences between chip development and commercial construction. We suspect that this is partially because the workshop participants (all engineers) had all observed buildings going up, and emphasizes the importance of finding analogies and examples familiar to the participants.

Both internal and external concurrence relationships were described and illustrated in all of the workshops even though each workshop developed descriptions for only one type of relationship. This was considered important to prevent the experts from commingling internal and external relationships in their descriptions. Although both types of relationships were described more time was spent explaining and illustrating the particular type (internal or external) to be developed in that workshop.

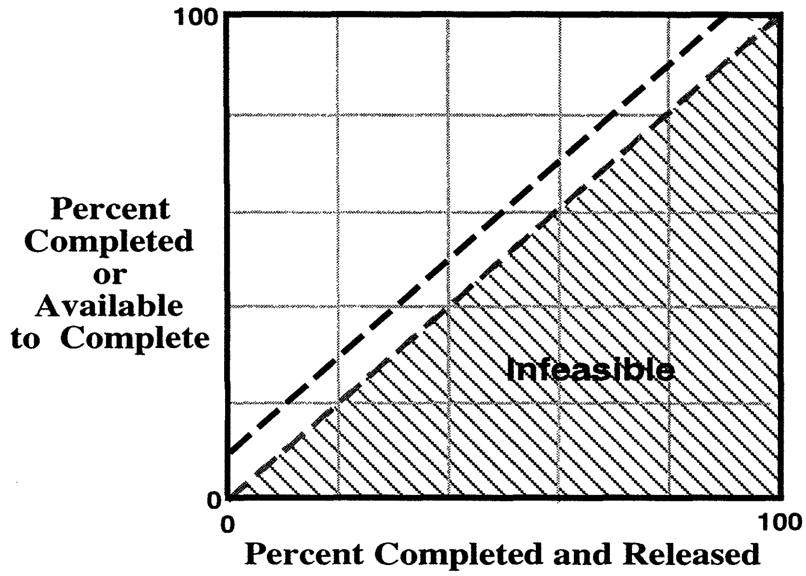

Figure 4: Steel Erection Example of a Graphic Description of an Internal Concurrence Relationship

Description Phase

4. Visual description: Experts were given three to five minutes to develop a visual description of the process. The redirection of expert's attention toward the facilitator indicated when this step was completed.

5. Verbal description: A review of the informal "Process Story Notes" sections of the worksheets completed by the experts (see appendix for examples) indicates that process images can take several forms. Most experts disaggregated the phase or pair of phases into development activities performed on a stable set of development tasks and important events in the phase such as product hand-offs and approvals. These were typically described with lists though some experts wrote in story form. Examples include:

- "From rough block diagram + biz [business] plan (20%) Design can begin top-level architecture and block definition (20%)"
- "Begin vector generation as soon as possible. If a cell completes then look at it from test perspective."
- "Once have relevant chardata [product characterization data] can set specs [specifications]."

Several experts linked disaggregated activities in their notes by estimating the availability of work each allowed in subsequent activities. Other experts estimated fractional contributions of each activity to completing the phase. A few experts listed combinations of activities and product components which are addressed concurrently during the phase.

6. Textual description: In addition to notes of their verbal descriptions, anchor point descriptions were the primary form of textual description. These were represented by a set of coordinates which would be plotted as points on the graphic frame and identifying notes describing the basis for the anchor point. One expert's textual description of the anchor points in the external concurrence relationship between the product definition and design phases is shown in Table 2 below.

Percent of Upstream Tasks Released	Percent of Downstream Tasks Completed or Available to Complete	Notes
0	0	Enabled
10	20	System definition - allows start bench coding
70	50	General functionality defines architectural design
100	100	Detailed operation allows internal block coding & all other steps to layout

Table 2: One Expert's notes describing Anchor Points of the External Concurrence Relationship between the Product Definition and Design Phases

The written examples based on the building project proved to be valuable aids to the experts while developing their own concurrence relationship descriptions. Eighty-seven percent of the relationship descriptions (20 of 23) included separate textual descriptions of anchor points. In two of the relationship descriptions in which anchor points were not specified they were included in the verbal or graphic descriptions.

7. Graphic description: With only one exception (described in the next step) the experts had little difficulty describing the relationships graphically. Figure 5 shows five graphic descriptions of the external concurrence relationship between the design and prototype test phases of the Python project. The five descriptions have very similar anchor point output values (Percent of Test Prototype Tasks Available to Initially Complete) at the extreme input values (0 and 100% of Percent of Design Tasks Released) but vary more between these anchor points, as one would expect.

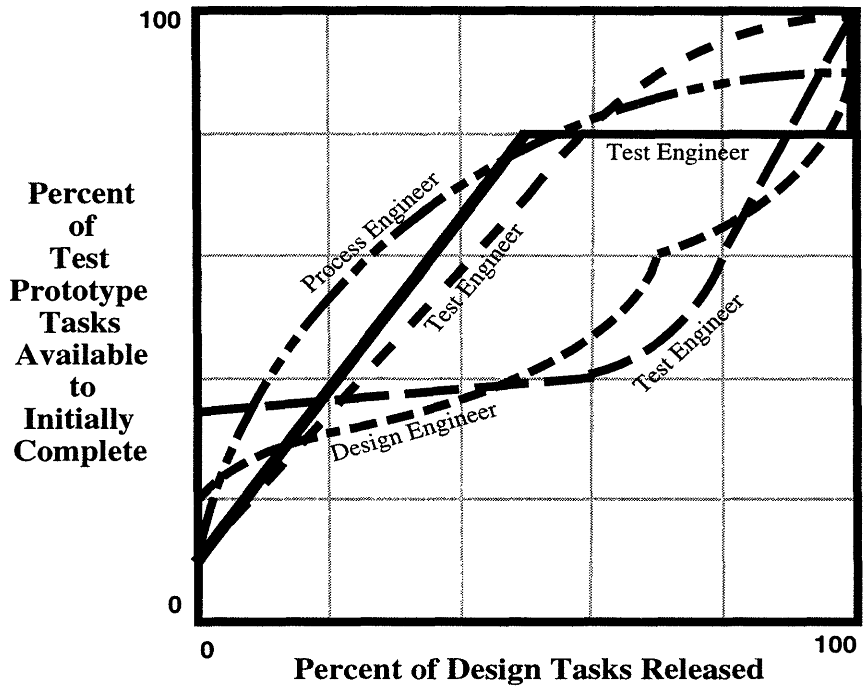

Figure 5: Five Graphic Descriptions of an External Concurrence Relationship between the Design and Test Prototype Phases

Discussion Phase

8. Examine individual descriptions: The examination of individual descriptions began with a verbal account by each expert of the basis for their graphic description. Some experts described their estimates during the discussion phase in the form of Gantt charts (Moder, Phillips and Davis, 1983; Levy, Thompson and Wiest, 1963) based on work units instead of time units. As an example the following description captures the verbal descriptions given by the process experts of the internal concurrence relationship of the design phase of the Python project, which produces the software code used to lay out the physical features of the computer chip: The code to be produced is organized into seventeen blocks (code modules). A few of these blocks of code must be designed and written before other blocks can be started. Therefore only these initial blocks (estimated to be 20% of the code) can be worked on at the beginning of the design phase. It's not feasible to begin work on the other blocks of code until the initial blocks are nearly complete. When the initial blocks are complete, most of the remaining code can be developed. When most of the blocks of code have been written the work of integrating them into a single operational program begins. Integration is fundamentally less parallel, producing a flat tail on the right side of a graphic description. The graphic descriptions of this relationship developed individually by three experts are shown with the dashed lines in Figure 6.

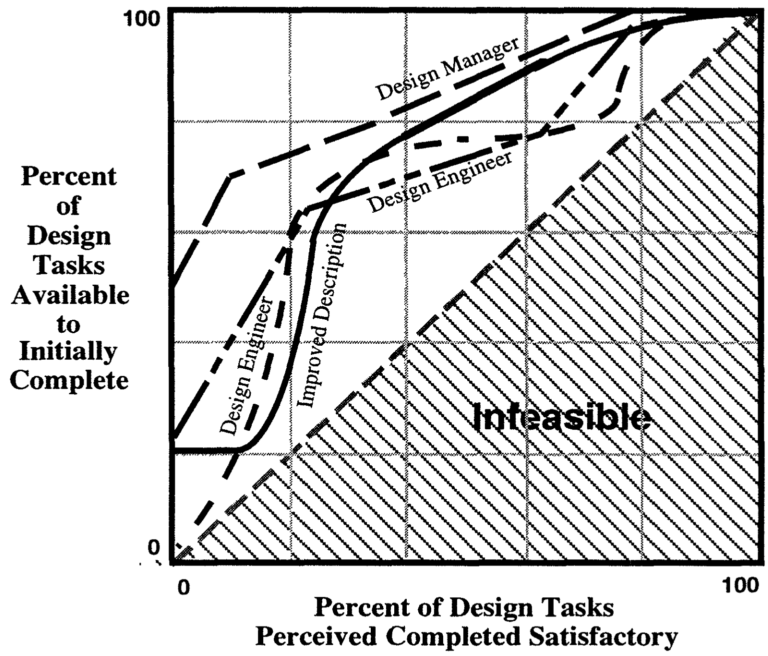

Figure 6: Four Graphic Descriptions of the Internal Concurrence Relationship of the Design Phase

The verbal descriptions added richness to the graphic descriptions by improving the modeler's and expert group's understanding of the mental model which formed the basis of the relationship description. In one case an expert was unable to construct a useful mental image of the process for the development of an internal concurrence relationship. The facilitator was able to assist the expert to build a description by asking the expert questions to disaggregate the work in the phase into availability-based units, tag the units with meaningful titles, quantify and then causally relate those units based on the approach used in the Design Structure Matrix (Smith and Eppinger 1997). These units were then used to identify anchor points in the expert's mental model which then served as the basis for a graphic description.

9. Compare descriptions: Differences among experts' descriptions provided the opportunity for testing and improvement. The descriptions of the internal concurrence relationship of the design phase (Figure 6) provide an example of how experts clarified and improved their graphic descriptions based on their discussion. The three experts were in general agreement with the verbal description of the relationship (see above) despite the differences in the three graphic descriptions. A discussion led by the facilitator resulted in the experts deciding that a horizontal portion at the beginning of the phase would improve the description by capturing the fact that most code blocks could not be started until the initial 20% were nearly complete. Based on this discussion an improved graphic description was developed (the solid line in Figure 3).

Differences among descriptions also identified differences among the experts and suggested causes for those differences. Consider the external concurrence relationship between product definition and design (Figure 7). Product architects and marketing representatives gradually define the requirements for the new product. As they release these the designers can begin to code the software which generates the chip layout so that it provides the specified functionality. Four experts, two from the upstream phase (one from strategic marketing and one product architect) and two from the downstream phase (a designer and design manager) participated in the workshop. The strategic marketing representative was the participant farthest upstream in the product definition/design portion of the Python project. His estimate suggested the most concurrence, implying little product definition work needed to be completed and released before designers could usefully do most of their work. The product architect, whose work is also upstream of design, also suggests that design can begin after only a small fraction of the product specifications has been released. In contrast the manager of the design phase and the designer believe the degree of potential concurrence is significantly less, estimating that roughly half the product specifications must be released before any significant design work can begin.

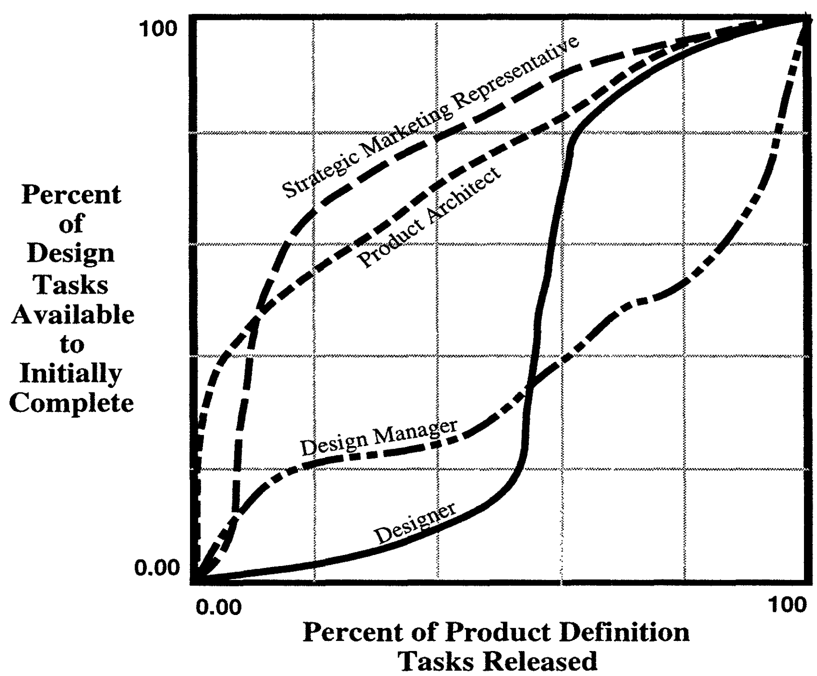

Figure 7: Four Graphic Descriptions of the External Concurrence Relationship between the Product Definition and Design Phases

Of particular interest in this example is that the team member who actually performs the design work (the designer) and the participant providing the basis for the designer's work (the strategic marketing representative) differ in their perceptions of the rate at which the design work can be done by over fifty percent of the design scope throughout most of the design phase. Such differences identify disparities in the mental models of team members which may be high leverage areas for improvement. Marketers believe design work can begin very early, while product attributes are still vague and evolving, while designers believe they must have detailed and stable specifications to do their work. This gap leads to conflict. In fact, the identification of this disparity in perspectives led to vigorous and useful discussion and helped the different parties come to a better understanding of the source of prior conflicts between their groups.

Using the Results of the Elicitation Method

Our method generates several useful products including multiple independently-generated parameter descriptions, expert reasoning behind those descriptions, comparison and testing of parameter descriptions by peers, communication among experts and the identification of areas of team mental model consistency and inconsistency. We used the descriptions generated by our elicitation method in several ways to improve our modeling.

- Verbal and textual descriptions provided data for triangulation with previously collected interview data on the structure and parameterization of the development process in the Python project. This improved structural model validity (Barlas, 1996; Forrester and Senge, 1980).

- Behavior pattern validation was improved through better model calibration by using expert knowledge instead of modeler estimates of critical relationships.

- Model analysis was improved by using differences in the expert's assessments to select the ranges of variation in parameters and relationships for sensitivity testing.

- Structural behavior validation (Barlas, 1996) was enhanced by setting limits on the extreme conditions of important model parameters. For example Figure 8 shows consistency among four descriptions of the internal concurrence relationship of the test prototype phase. None of the four descriptions extend above the 45° line crossing the vertical axis at 50% of Test Prototype Tasks Available for Initial Completion. Therefore this is a more reasonable value for extreme conditions testing than a totally concurrent relationship described by a horizontal line along the upper axis of the graphic frame.

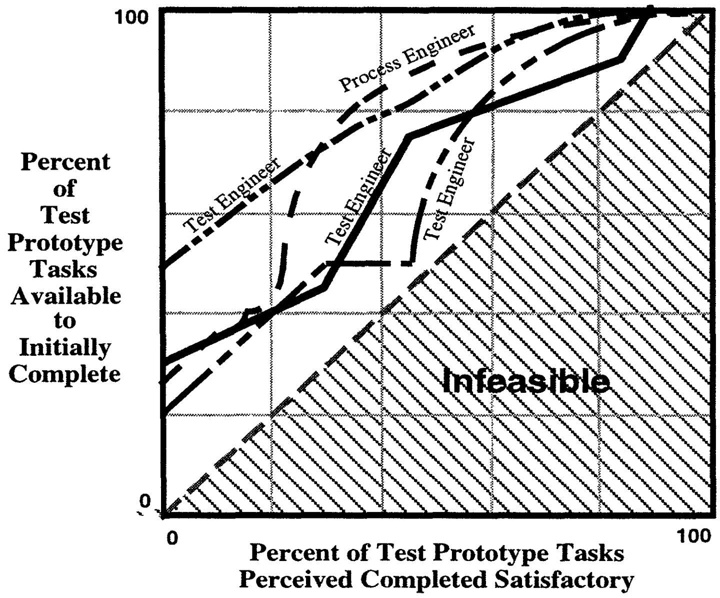

Figure 8: Four Graphic Descriptions of the Internal Concurrence Relationship of the Test Prototype Phase

- The process significantly improved formal model credibility in the eyes of the participants by involving those responsible for the system in the modeling process, acknowledging and honoring participant expertise and making special efforts to incorporate that expertise into the model. Developing such understanding is essential to successful transfer of insight, the development of systems thinking skills among the client team, and ultimately, successful implementation of model-based policy recommendations.

We also used the results of our method to analyze and improve expert mental models. We derived valuable insights from the similarities and differences among estimates of the same concurrence relationship. The various descriptions of each concurrence relationship indicated both areas of agreement and conflict among the mental models of the Python development team. For example the variation in estimates of the external concurrence relationship linking the design and test prototype phases (Figure 5) is less than for the external concurrence relationship which links the product definition and design phases (Figure 7). This indicates that the Python team's mental models are more consistent for the first relationship than the second.

The codification of expert knowledge and discussion of descriptions provided a vehicle for improving shared mental models, as suggested by Morecroft (1994). The examination of individual mental models at the level of specificity facilitated by our method in a non-threatening group context provided a way to investigate the causes of disparities in the beliefs of team members and resolve differences in their mental models. The experts in our workshops recognized the potential of using our elicitation method to identify areas of team mental model inconsistency and therefore potential high leverage points for improving the product development process. Combining parameter sensitivity and degree of consistency may provide an effective means of identifying effective system features for improvement. This can also help to avoid group-think and premature convergence (Vennix et al., 1994).

Evaluation of the Method

Our application of the elicitation method acts as an initial test of our hypothesis concerning the use of successive knowledge transformations across description formats as an improved means of eliciting expert knowledge for modeling. The benefits achieved for formal modeling of the Python project and the Python development team suggest that our method can improve expert knowledge elicitation for formal modeling and mental model improvement.

Our method includes several aspects which are new or potentially need to be customized for effective application in a particular modeling project. We assess our method as follows.

1. Knowledge held primarily in mental models is usually not described in other formats because of its complex and tacit nature. The method uses multiple formats to elicit and capture expert knowledge from several descriptive perspectives. These multiple formats are more likely to capture portions of expert knowledge which might be lost with a single format - single step elicitation method.
2. The use of four description formats adds richness which improves information quality through triangulation. This triangulation occurs in two places: within individual experts as they seek consistency among their descriptions of a particular relationship and across experts when they compare their different descriptions.
3. The generation of a graphical representation through a succession of smaller steps (image to words to anchor points to graph) rather than asking people to simply "draw the relationship" improves knowledge elicitation by reducing the cognitive processing required of system experts in each step. Multiple formats and steps also slow the elicitation process, thereby providing more time for reflection and revision.

4. Explaining and providing complete documentation of the steps to be performed by the experts using an example from a familiar but different context significantly improves the quality of the descriptions and the experience of the experts.
5. The method focuses modeling efforts on knowledge that experts consider both important and proprietary in that they are the holders and users of the knowledge. Prior work documents the benefits of including system participants in modeling at the conceptual level; our method engages experts more fully by honoring the full range of participant expertise.
6. The discussion phase provides immediate benefits to experts by allowing them to share and compare mental models in a form which facilitates learning through the investigation of underlying assumptions.
7. The process of describing and comparing individual descriptions in a group of peers increased error checking.

Conclusions

Eliciting expert knowledge for formal modeling raises different challenges than elicitation for conceptual modeling or consensus-based decision making. Our method focuses on the elicitation of expert knowledge in a form suitable for formal modeling to help experts make more of their tacit knowledge explicit and available for examination and improvement. We use our method to develop estimates of specific system relationships by individual experts which are the basis for description testing and mental model improvement. The method was found to be an effective tool to improve formal modeling and to help a development team improve their mental models.

Improving our ability to make tacit expert knowledge explicit and usable for formal modeling and mental model improvement can have important effects on both research and practice. Researchers can use the increased quantity, quality and improved understanding of expert system knowledge derived in this way to build more complete and accurate models. Practitioners can increase their awareness, understanding and use of the tacit knowledge which generates organizational behavior and often leads to organizational dysfunction.

Future research can assess our method by comparing it with other elicitation techniques such as the qualitative approaches used in conceptual model building. The broader application of our elicitation method can be tested by applying it to other types of model parameters and relationships, and with experts and contexts different from the product development setting used here. The integration of the techniques we have used with other elicitation techniques may provide the basis for more advanced elicitation methods.

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Appendix: Sample Worksheets from Elicitation Workshops

Notes

1. The handwritten notes produced by the experts on the first page of the worksheets have been transcribed onto identical forms for increased legibility and to preserve confidentiality. Explanations of abbreviations and jargon are provided in brackets, [].

2. The term "Internal Precedence Relationship" was used in the example to refer to an Internal Concurrence Relationship. The term "External Precedence Relationship" was used in the example to refer to an External Concurrence Relationship.

3. The word "Infeasible" and the shading of the lower right half of Internal Concurrence Relationship graphic frames (see Figures 4, 6 and 8) were added subsequent to the example workshop to facilitate the explanation of the infeasability of relationships described by curves in this area. See Ford and Sterman (1997) for an explanation of this constraint.

INTERNAL PRECEDENCE WORKSHEET

Development Activity described: PPS [Test Product Prototypes]

Position held by author: [Process Engineer]

PROCESS STORY NOTES:

Must wait for fab [fabrication] for all other,

Once have probecard/program/wafers can sort,

once sorted can assemble

once hardware/programs/assembled can do char [product characterization],

once have relevant chardata [product characterization data] can set specs [specifications]

once specs [specifications] set and apps [applications] OK can complete

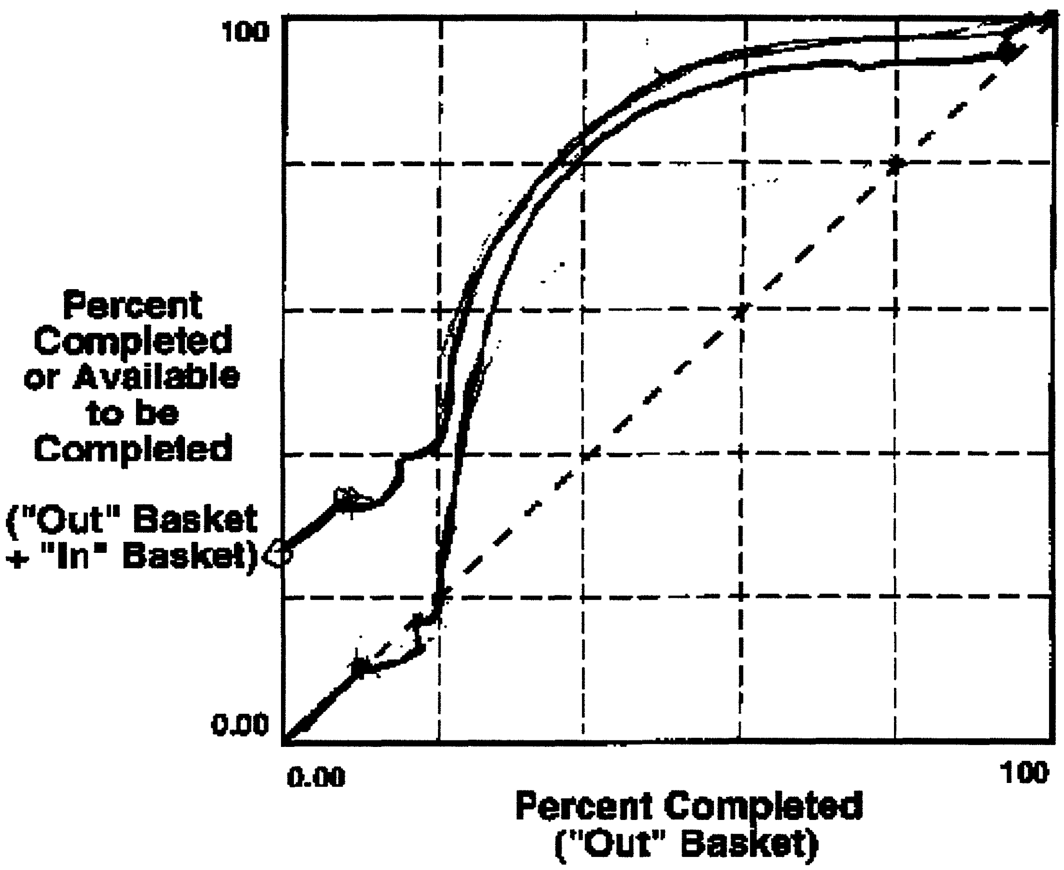
ANCHOR POINTS IN TABLE:

Percent Completed	Percent Completed or Available to Complete	Notes
0 -->	10%	Fab [fabrication]
10%	15%	Sort
15	20	assembly

INTERNAL PRECEDENCE WORKSHEET

Development Activity described: PPS [Product Prototype Test]

Position held by author: Process Eng [Process Engineer]



NOTES:

1. See Figure 8 for a comparison of the relationship described above with other descriptions of the same relationship.

2. This example illustrates the results of repeated reflection by an expert through our method. The textual description in the form of the anchor points (step 6) shown on the first page of this description was adjusted by the expert in the formation of the initial graphic description (step 7), shown by the lower line in the graphic frame above. The initial graphic description was improved when examination (step 8) revealed the unfeasibility of a portion of the initial graphic description, resulting in the final description shown by the upper line in the graphic frame above. See Ford and Sterman (1997) for an explanation of the unfeasible portion of the graphic frame.

EXTERNAL PRECEDENCE WORKSHEET

Upstream Development Activity: Product Definition

Downstream Development Activity: Design

Position held by author: Product Architect

PROCESS STORY NOTES:

1. Product "straw-man" complete - can begin high-level design & acquisition of needed design info [information] (e.g. cells, tools)

2. Feedback incorporated into straw-man, producing 1st-cut product def'n [definition]

3. Incremental product-def'n [definition] refinement,

4. Hand-off complete

ANCHOR POINTS IN TABLE:

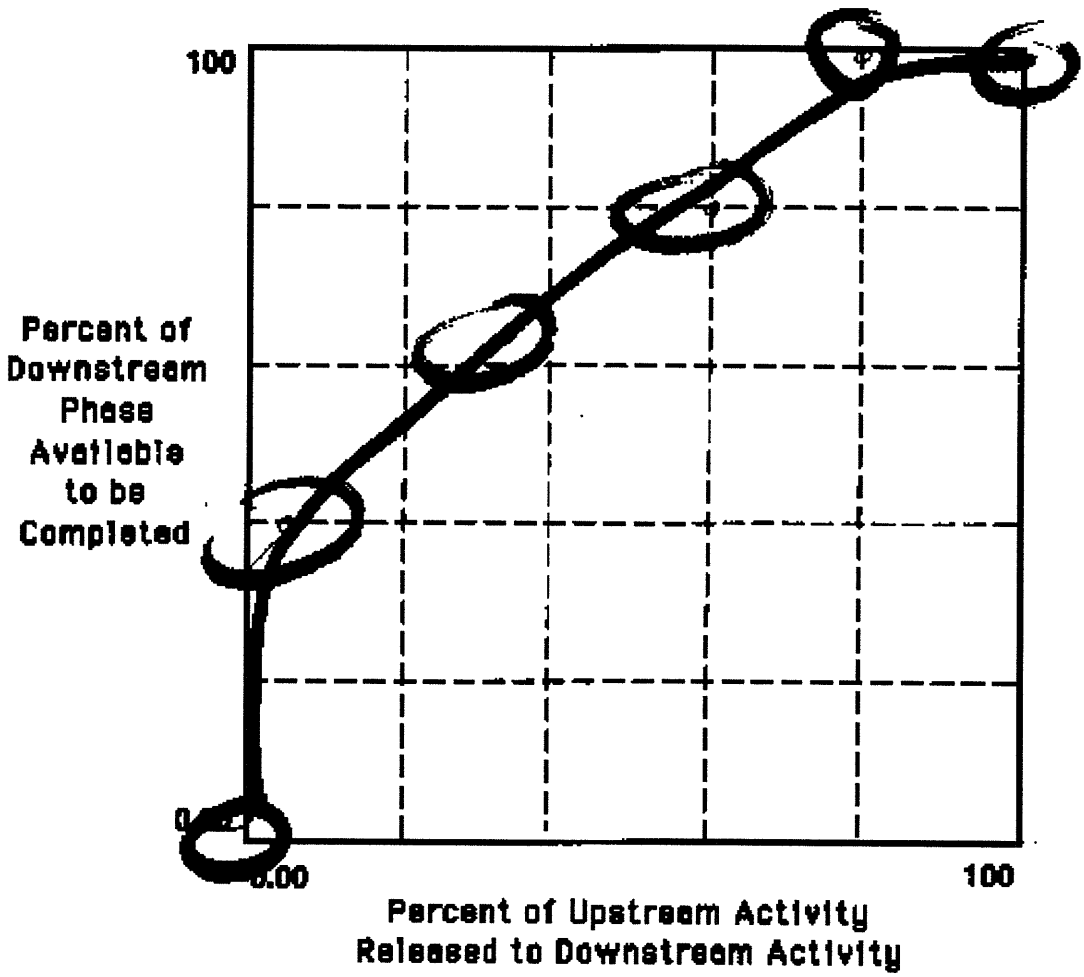
Percent of Upstream Tasks Released	Percent of Downstream Tasks Completed or Available to be Completed	Notes
10	40	1. [see above]
35	65	2. [see above]
60	85	3. [see above]
80	100	

EXTERNAL PRECEDENCE WORKSHEET

Upstream Development Activity: Product Definition [Product Definition]

Downsteam Development Activity: Design [Design]

Position held by author: Product Architect [Product Architect]



NOTES:

1. See Figure 7 for a comparison of the relationship described above with other descriptions of the same relationship.

EXTERNAL PRECEDENCE WORKSHEET

Upstream Development Activity: Product Design

Downstream Development Activity: PPS [Product Prototype Testing]

Position held by author: [Test Engineer]

PROCESS STORY NOTES:

- Design starts block development,

test has acquired Product Knowledge from Arch [product architecture] Review

- Design complete Block 1, Test starts DFT [testing] on Block 1

continue loop until Design complete, Along the way:

| Develop test plan (TEP)

| Develop char [product characterization] plan ( )

| Develop final test plan (Production

- FAB [fabrication] cycle / Complete simulation / test programs

ANCHOR POINTS IN TABLE:

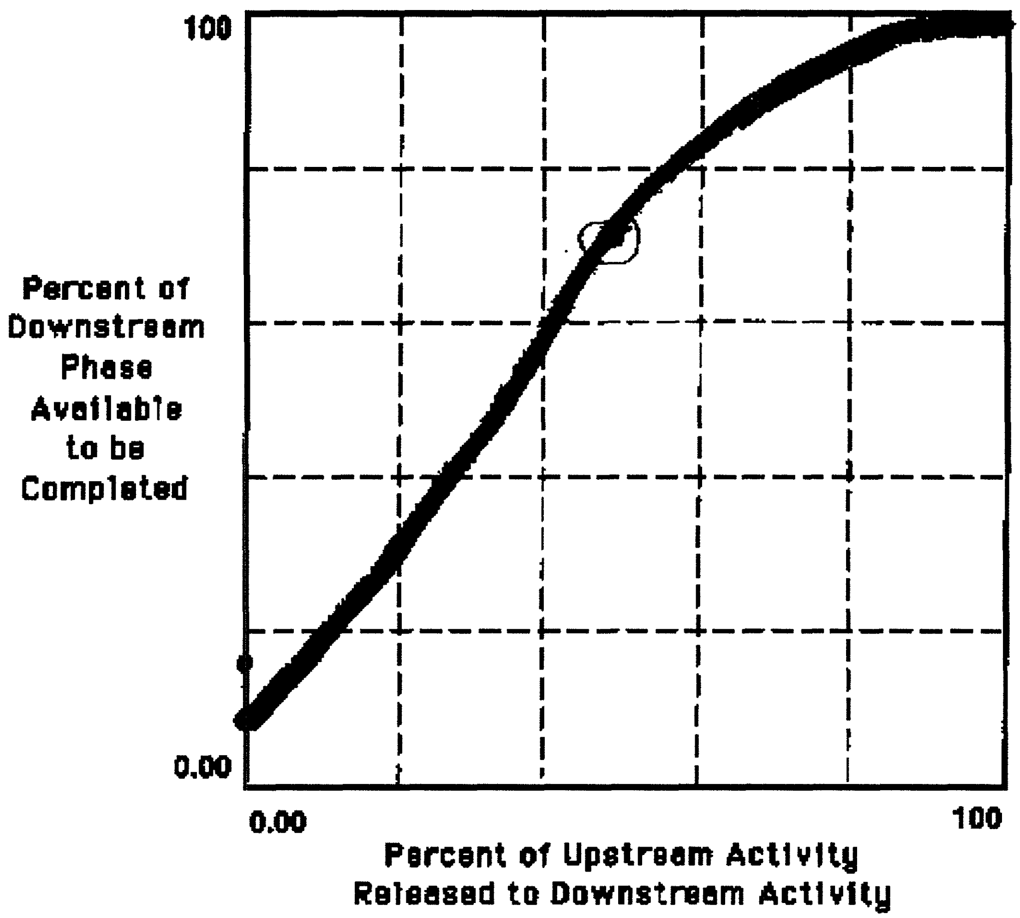
Percent of Upstream Tasks Released	Percent of Downstream Tasks Completed or Available to be Completed		Notes
0	10	10	Product Knowledge
20	15	25	DFT [testing] anchors
50	20	75	DFT + test plans
75	25	90	Final test plan for char/PPT/wafer sort
100	35	100	DFT complete.
	complete	% can complete	

EXTERNAL PRECEDENCE WORKSHEET

Upstream Development Activity: Product Design [Product Design]

Downsteam Development Activity: PPS [Product Prototype Test]

Position held by author: [Test Engineer]



NOTES:

1. See Figure 5 for a comparison of the relationship described above with other descriptions of the same relationship.