A CRITICAL REVIEW OF DIAGRAMING TOOLS FOR CONCEPTUALIZING FEEDBACK SYSTEM MODELS

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ABSTRACT

During the development of the field of System Dynamics, the causal loop diagram has risen to prominence as the diagraming tool for conceptualizing feedback system models. This paper challenges the prominent role of causal loops in conceptualization and offers instead two new tools, the subsystem diagram and the policy structure diagram.

Causal loop diagrams are argued to be weak tools of conceptualization. They do not correspond closely to common mental models of social and industrial systems, and are therefore inefficient as a channel of communication between a formal model and its database of descriptive information. Causal loop diagrams do not adhere to the basic structuring principles of feedback systems, nor do they represent explicit decision-making processes and therefore lack the organizing power that should be expected of a conceptualizing tool. Their main strength is in providing an overview of loop structure, which is most useful in behavior analysis, not conceptualization.

Two new diagramming tools are proposed for overcoming the weakness of causal loop diagrams. The subsystem diagram shows major organizational divisions in a social or industrial system and is useful in boundary definition. The policy structure diagram shows the stock-and-flow structure of a subsystem and major policies with their supporting information flows. The policy structure diagram is designed to improve the efficiency of communication between formal and mental models, and adheres strictly to the structuring principles of feedback systems. The use of the new conceptualizing tools is illustrated using material derived from a corporate marketing strategy project.

BACKGROUND

During the evolution of the field of System Dynamics, causal loop diagrams (or influence diagrams) have come to play a central role in the conceptualization and communication of feedback structure. In this paper, several arguments are raised that challenge the central role of causal loop diagrams. In doing so, the intention is not to bring into question the general usefulness of the causal loop diagram, but rather its specific use in basic conceptualization. The causal loop will always play an important role in education, as it is a powerful and concise way of conveying the concept of feedback structure. Causal loop diagrams are also powerful tools in behavior analysis and policy design. But as a tool for organizing the descriptive data of mental models, causal loop diagrams are flawed. They can lead to poor model formulation and do not have the resolution to portray structure at the level of real physical and decision-making processes.

Firstly, a brief history of the portrayal of feedback structure is presented. In this history an attempt is made to identify the point at which the causal loop diagram emerged as a distinct concept (it was not present from the outset) and to trace the path by which it came to be most closely associated with conceptualization. Secondly, there is a discussion of the problems with causal loop diagrams that focuses particularly on their weakness as an organizer of descriptive information. Next, two new conceptualizing tools are presented, the subsystem diagram and the policy structure diagram. The subsystem diagram shows the organizational divisions in a social or industrial system. The policy structure diagram identifies the major policies within each subsystem and clearly distinguishes the information network from the conserved stock-and-flow network. Finally, there is a discussion of the results of using the new tools in a corporate project and in teaching.

BRIEF HISTORY OF THE PORTRAYAL OF FEEDBACK STRUCTURE

Flow Diagrams and the Portrayal of Substructure

Forrester's *Industrial Dynamics* (1) lays the conceptual foundations for the field of system dynamics. It is interesting to note that the book does not contain a single causal loop diagram, nor any mention of the idea of portraying feedback structure in terms of simple cause-and-effect links. Instead, *Industrial Dynamics* uses flow diagraming symbols to portray system structure, where in Forrester's words the diagram "represents an intermediate transition between a verbal description and a set of equations."

In Chapter 15 of *Industrial Dynamics*, Forrester uses flow diagrams to describe a model of a production-distribution system. The system is developed and presented in pieces. For example, in describing the retail sector (15.5.1), Forrester begins first with diagrams and equations for the basic stock-and-flow structure of the system. Then order filling is added, followed by formulations for delivery delay,

desired inventory and smoothed sales, and finally, the purchasing decision. Flow diagrams of the detailed component parts are presented, but there is little attempt to provide an overview of the feedback structure. The visual complexity of a system flow diagram is too great to allow major feedback loops to be shown within the confines of a single page.

Loop Structure Portrays an Overview

One of the first published examples of loop structure occurs in Forrester's paper "Market Growth as Influenced by Capital Investment" (2). In this paper, and simultaneously in the text *Principles of Systems* (3), Forrester proposed the concept of a hierarchy of structure that could be used for organizing the model-building process. At the top of the hierarchy is the closed system within whose boundaries dynamic behavior is generated. Immediately below the closed system is the feedback loop, which Forrester describes as "the basic element from which closed systems are assembled". Feedback loops in turn comprise two fundamental variable types, levels and rates.

In "Market Growth", Forrester proceeds to illustrate this hierarchy of structure with an example in marketing. The first figure in the paper, which is reproduced in Figure 1, depicts the loop structure for sales growth, delivery delay, and capacity expansion in a corporation. Although the figure is not labeled as a causal loop diagram and does not use the polarity conventions of causal loop diagrams, it is nevertheless a concise representation of feedback structure and a clear prototype for later causal loop diagrams.

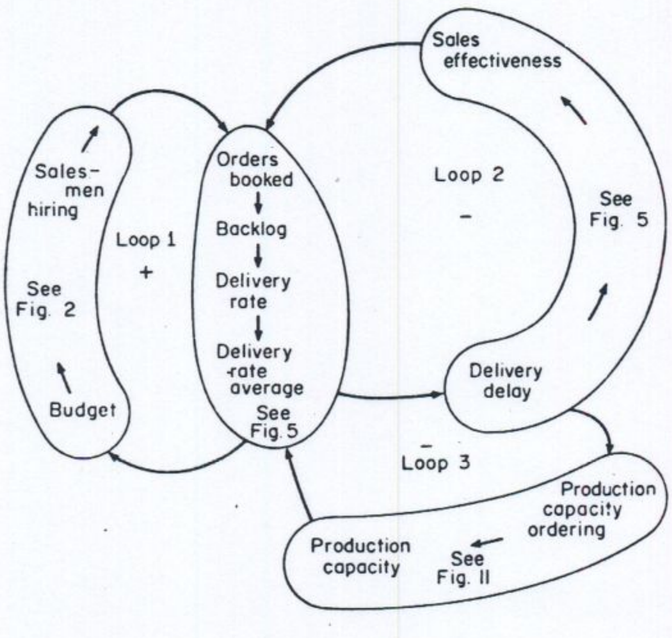

Figure 1. Loop Structure of Market Growth Model
(Reproduced from Forrester [2])

It is important, however, to emphasize that this prototype loop structure diagram does *not* represent the conceptual origin of the model described in the paper, but is rather the final and refined product of the conceptualization and modeling process. Although the figure appears early in the sequence of presentation, it almost certainly originated late in the modeling process and represents a distillation of the understanding of feedback structure that was derived by conceptualizing the parts of the system and simulating their interaction. The diagram is cast at a very high level of abstraction relative to the real system it portrays. It would be exceedingly difficult to imagine that the loop structure Forrester depicted would be the product of a preliminary conceptualization effort on market growth.

After *Principles of Systems* and "Market Growth", the idea of displaying loop structure seems to have taken firm root. A diagram of loop structure is an extremely convenient and concise way of showing the interconnectedness of a complex system. A diagram of loop structure provides an overview of the system that is impossible to achieve with conventional flow diagramming tools. For these reasons, loop diagrams were quickly integrated into the teaching and methodology of system dynamics.

However, the basic contention of this paper is that the role assigned to causal loops as the field continued to develop ran counter to their original use in the "Market Growth" paper. Causal loop diagrams belong logically toward the end of a study rather than at the beginning. They are a powerful tool for summarizing insights about structure and behavior. They are not powerful tools for basic conceptualization.

Emergence of the Causal Loop Diagram

Tracing through the published texts and working papers that followed in the wake of *Principles of Systems*, the ascendency of the causal loop diagram increases, often to the exclusion of other methods of portraying feedback structure. The text that has probably done the most to foster the widespread use of causal loop diagrams is Goodman's *Study Notes in System Dynamics* (4). *Study Notes* begins with a full explanation of causal loop diagrams and the methods used to determine their polarity. Causal loop diagrams are used throughout the text in conjunction with flow diagrams and are explicitly stated to be a tool for conceptualization.

> Causal loop diagrams can be most useful during the early stages of model conceptualization, as they help identify and organize principal components and feedback loops of the system under study . . . Causal loop diagramming simplifies the transformation of verbal description into feedback structure. Such diagramming also readily reveals the loop structure of complex models to people unfamiliar with flow diagrams or DYNAMO notation.

Randers (5), in a mature and insightful paper on the modeling process, also assigns great importance to the causal loop diagram as a conceptualizing tool

> Having specified the reference mode, the model should identify the fundamental real-world mechanisms assumed to produce the reference mode. He should select and describe the smallest set of feedback loops considered sufficient to generate the reference mode, that is, select the basic mechanisms . . . A quick sketch of the basic mechanisms in causal diagram form may focus the modeler's thoughts and help him visualize the system boundary.

Randers is careful, however, not to assign too much explanatory power to the causal loop, pointing out in a later paragraph in the same paper:

> The belief that the basic mechanisms can actually reproduce the reference mode remains an assumption until model simulation proves this dynamic hypothesis to be correct. The modeler should therefore build an initial model, consisting of the basic mechanisms, and simulate it to test the dynamic hypothesis, that is, to check whether the basic mechanisms can actually generate the reference mode.

With these two statements Randers points to what seems an inherent contradiction in causal loops as a conceptualizing tool. A causal loop diagram in isolation from a simulation model and a more complete structural system diagram is widely acknowledged to be an unreliable indicator of system behavior. Even experienced modelers dealing with a new system and seeing it in causal loop form would not be prepared to predict the behavior that would result from any but the simplest sets of interlocking loops. Causal loop diagrams, therefore, are of use in conceptualization only to the extent that they portray system linkages. They provide no guarantee of support for a dynamic hypothesis. However, there are other tools of conceptualization that more readily generate system linkages and that are more consistent with most people's mental models of the pieces of system structure.

Coyle (6) in his text *Management System Dynamics,* has also assigned causal loops (or influence diagrams) to the role of conceptualizing tools, stating that the basic tool for developing a dynamic model is the influence diagram. In Chapter 3 of his text, Coyle proposes more advanced procedures for developing influence diagrams than the rather ad hoc methods used in *Study Notes*. He proposes five criteria to justify a causal link between variables in a system.[1] Furthermore, he describes a procedure called the "List Extension method" that guarantees closure of the causal loop and therefore a model that generates behavior endogenously.

Coyle's methods inject more conceptualizing power into causal loops by forcing the modeler to justify the rationale for each linkage. However, the added power does not entirely overcome the inherent weakness of the causal loop diagram as an organizer of the descriptive data of mental models.

WEAKNESSES OF CAUSAL LOOP DIAGRAMS IN CONCEPTUALIZATION

Little Correspondence Between Mental Model and Loop Structure.

Most people visualize social and industrial systems in terms of their component parts. People are able to provide adequate descriptions of component parts. Managers in a corporation can describe an inventory-control policy, a pricing policy, a capital investment policy, or financial and accounting procedures. They visualize their corporation in terms of policy groupings that correspond to functional areas. They rarely carry in their head a mental model that links the component parts together in a complex interlocking system. Causal loops are an emergent property of the coupling of component parts. To begin the modeling process with a tool that focuses on emergent properties seems inappropriate. The lack of correspondence between mental models and loop structure is almost certain to result in loss of valuable information about real-world structure and linkage.

The argument above is not intended to downplay the importance of a feedback viewpoint. It is, of course, important for people to become aware of the feedback structure of the systems they manage, for it is out of the structure that problem behavior arises. However, the importance of the feedback viewpoint should emerge naturally from piecing together the components in an orderly manner.

No Explicit Representation of the Decision-making Process

A causal loop diagram does not explicitly represent human decision-making processes. It is not possible to look at a causal loop diagram and deduce where decisions are being made, how responsibilities are distributed, and what information different decision makers deem important in their part of the system. By ignoring the existence of decision-making processes, causal loop diagrams overlook real features of organizations that can lend precision to the generation of system linkages. Decision-making processes, or policies, are nodes of the information network. They are the points in the organization that information is collected, processed, and dispersed. Recognizing their role as information processors, we can be discriminating about the quantity and content of information that is likely to be used at any policy point. The causal loop diagram fails to make use of decision-making features of the real system that are valuable in conceptualization.

No Discrimination of the Elements of Structure

Causal loop diagrams provide no discrimination of the basic elements of feedback system structure. A causal loop diagram does not differentiate between the conserved stock-and-flow network and the information network that contains decision making. As a result, there are no building blocks from which to assemble larger structures, and there are no structuring principles to say which links are permissible and which are unlikely to exist. A causal loop diagram is therefore a much weaker organizing tool than something like a system flow diagram, which properly differentiates the conserved and information networks. But organization is the essence of conceptualization.

Loop Structure Not a Reliable Guide to Behavior

The weak relationship between loop structure and behavior has already been mentioned. Introductory system dynamics courses often focus on the behavior generated by negative and positive loops. Such an introduction to feedback system behavior is, of course, valuable. However, it is a mistake to infer that complex system behavior can be reliably deduced from a picture of coupled positive and negative loops. The only reliable tool for understanding behavior is simulation (or analytical solution in the few practical instances where a solution can be found). If causal loop structure in isolation is an unreliable guide to behavior, there seems to be little point in demanding a causal loop diagram in the early stages of conceptualization.

Ambiguities in Defining Loop Polarity

A causal loop diagram in isolation is often ambiguous about

loop polarity. The ambiguity can be viewed as an extreme case of the general unreliability of a causal loop diagram as an indicator of behavior. Richardson (7) has explored the problem of ambiguous polarity in some detail:

> The crux of the problem with causal loop diagrams, is that they make no distinction between information links and rate-to-level links. That simplification is usually thought to be one of the advantages of causal loop diagrams, but it has a rather dramatic disadvantage: in cases involving rate-to-level links, the standard characterization of positive and negative polarities in causal loop diagrams is false.

Richardson proceeds to develop several examples that clearly demonstrate the problem of ambiguity. The assignment of polarity to individual rate-to-level links is shown to be a major cause of error in the assignment of loop polarity. In addition, Richardson argues that hidden loops and net rates in causal loop diagrams make definitions of loop polarity difficult.

Published Diagrams Belie the Original Conceptualization Process

A factor that seems to lend weight to the use of causal loop diagram for conceptualization is that such diagrams are often the only picture of system structure accompanying published results of system dynamic studies. Since causal loop diagrams can be so effectively used to provide an overview of the model and to analyze behavior (as in Forrester's "Market Growth" paper), the temptation is to think that the diagram is a suitable starting point for modeling. In many instances the diagrams are, in fact, the end point of modeling and represent a distillation of understanding which may have taken months or years to achieve. The clearest examples of causal loop diagrams found in introductory texts and educational material all fall into the category of being based on the hindsight of an existing model.

NEW TOOLS FOR CONCEPTUALIZATION

An effective tool for conceptualization should be an efficient organizer of the descriptive data of mental models. Efficiency would be achieved if system structure were portrayed in terms of real decision-making processes and in organizational units that are compatible with mental models. Furthermore, the conceptualizing tool must be capable of portraying an overview of system structure and must embody to the largest extent possible the structuring principles underlying feedback system models.

The major existing alternative to a causal loop diagram is a system flow diagram that specifies fully the physical flows, levels, auxiliaries and information flows of the system. The system flow diagram is superior to the causal loop diagram in the sense that it imposes structuring principles in the construction of the diagram. However, it is extremely difficult, in all but the simplest of models, to convey an overview of system structure with a flow diagram. Furthermore, a system flow diagram is a rather explicit pictorial model that limits fluid interpretation of the mental model. It is the fluid exchange between mental and formal model that is especially important in early conceptualization.

In the remainder of the paper there is a presentation of two new diagrammatic tools for conceptualization, the subsystem diagram and the policy structure diagram.

The Subsystem Diagram

The subsystem diagram shows the major subsystems included in the model. Subsystems correspond to organizational divisions in a social or industrial system. In a corporate setting, it is often useful to associate subsystems with functional areas such as marketing, pricing, accounting, capacity planning or manpower planning. In an economic setting, subsystems may be coupled into larger groupings such as the financial and banking sector, the household sector, the labor sector, and various industrial production sectors.

Subsystems, when properly selected, correspond well with mental models of system structure. They classify structure into organizational divisions that are familiar in the real world. People in corporations can identify with functional areas. Furthermore, subsystems are useful in defining the model boundary. It is often possible to eliminate entire functional areas in a corporate project when there is a consensus that the areas exert no significant constraint on the corporate activities under study. Subsystems can be used to communicate an overview of the model, making clear what is included and what is excluded from the study. A clear overview of structure is a very valuable product of any system dynamics study. It is the overview that most managers and administrators lack. A tool that provides an overview is valuable in establishing the two-way communication channel between mental and formal models that is essential to good modeling.

Figure 2 below shows the symbol adopted for a general subsystem. The shape of the symbol has been selected to avoid any ambiguity or overlap with standard system flow diagram symbols already in use.

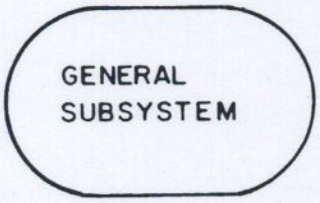

Figure 2. Symbol for a Subsystem

A Subsystem Diagram for a Manufacturing System

As an example of the use of a subsystem diagram, consider a model that might be used to address a classical manufacturing problem of production and ordering instability. Figure 3 shows a configuration involving three subsystems. At the top of the figure is a retail sector containing the inventory control and ordering policies of the retail network. The retail sector places orders on the manufacturing firm and receives shipments of goods in return. The manufacturing firm is depicted as two interacting subsystems, production and shipping control and labor procurement. The subsystems correspond to the two functional areas of the firm that are most closely associated with problems of production stability and manufacturing cost. The production and shipping control subsystem contains scheduling, inventory control, and forecasting policies of the firm. The labor procurement subsystem contains policies for manpower planning, hiring and layoff. The figure shows some of the major information and physical connections coupling subsystems, thereby providing an image of a complex system of mutual dependence and feedback. A well-

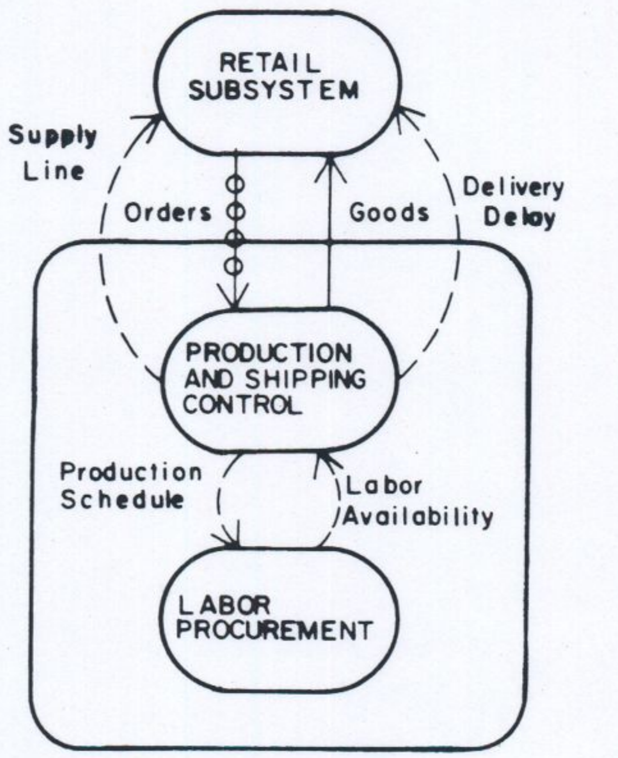

Figure 3. Subsystem Diagram for Manufacturing and Retailing

constructed subsystem diagram can reveal some of the large feedback loops that thread their way throughout an organisation and are often responsible for producing unexpected behavior in the system.

The Policy Structure Diagram

The policy structure diagram shows the internal structure of a subsystem. The diagram explicitly identifies the conserved stock-and-flow network in the subsystem and the information network. The diagram is similar to a system flow diagram, but is simpler.

Simplification is achieved in the information network by conceptualizing the network in terms of major policies, or decision functions such as inventory control, pricing, or manpower planning. Policies are deliberately selected to coincide with mental models of organization, which often consist of fragmented pictures of functional area responsibilities. Policies do not depict the detail of decision making that is usually shown in a system flow diagram. A policy structure diagram is, however, entirely consistent with a system flow diagram from the standpoint of adhering to basic structuring principles of feedback systems.

Figure 4 shows the basic building blocks of the policy structure diagram. In the upper half of the figure, the symbols for the conserved stock-and-flow network are shown: a level, physical flows, flow regulators, and the source and sink for the flows. These symbols are precisely the same as used in full system flow diagrams. In the lower half of the figure, the symbols for the information network are shown. The information network depicts information flows and the policies that process information. Policies are represented by a circular symbol or a box attached to a flow regulator.[2] The different symbols distinguish those policies that directly regulate physical flows from those that reside entirely in the information network and are an input to another policy in a more complex decision process.

A policy is a function of its supporting information flows. The exact functional form is not specified, even in outline, and could involve information delay functions as well as the more usual algebraic and table functions. Thus, a policy might encompass a large number of more basic auxiliaries, constants, and information levels than would appear on a full system flow diagram. By avoiding excessive formulation detail, the policy structure diagram allows for a flexible interpretation of a mental model in the early stages of conceptualization. Moreover, each policy can later be isolated and specified in full detail in equation formulations (or conventional flow diagraming symbols), thereby allowing hierarchical development of the model.

Policy Structure Diagrams – More Disciplined Strategy for Developing System Linkages

The policy structure diagram focuses centrally on policy (decision making) and the information network that supports policy. This focus leads to a more disciplined strategy in generating system linkages than is available from the use of causal loop diagrams.[3] In causal loop diagramming, links emerge in a 'brainstorming' process[4] guided chiefly by experience and a background feel for feedback structures that might interact to 'explain' the observed or hypothesized behavior. The process seems to be rather ill-defined, intuitive, and likely differs considerably from one practitioner to the next.

The generation of linkages in a policy structure diagram involves a two-step process. First, policy symbols are drawn (usually taking one subsystem at a time) to delineate the decision-making responsibilities of the organization. This is a relatively simple and unambiguous step, but one that does not occur in causal loop diagraming because decision making is not the focus of conceptualization. In the second step the information network is created using policies as nodes for information links. Links are generated by posing questions such as: What information is available at a particular point of decision making in the system? What information would be relevant to the decision-making process in question? With which parts of the overall system is the area containing this policy in closest communication? What information is *not* available at this point in the system, and why not? How much information is entering the policy, and is it possible to collect and meaningfully process such information? What is the quality of information available at this point in the system, and what distortions are likely to arise? Using a policy structure diagram, we can pose a whole series of questions that refine our concept of the decision-making process and the information on which it depends. By pursuing such reasoning at each policy point in the system, a network of communication naturally emerges out of consideration of real decision-making processes.

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.

With a policy structure diagram it is possible to pin down the network of communication with more confidence and greater precision than with causal loop diagrams. Since the network of communication defines the feedback character of the system, the policy structure diagram should be a more powerful tool for conceptualization. In particular, the series of questions

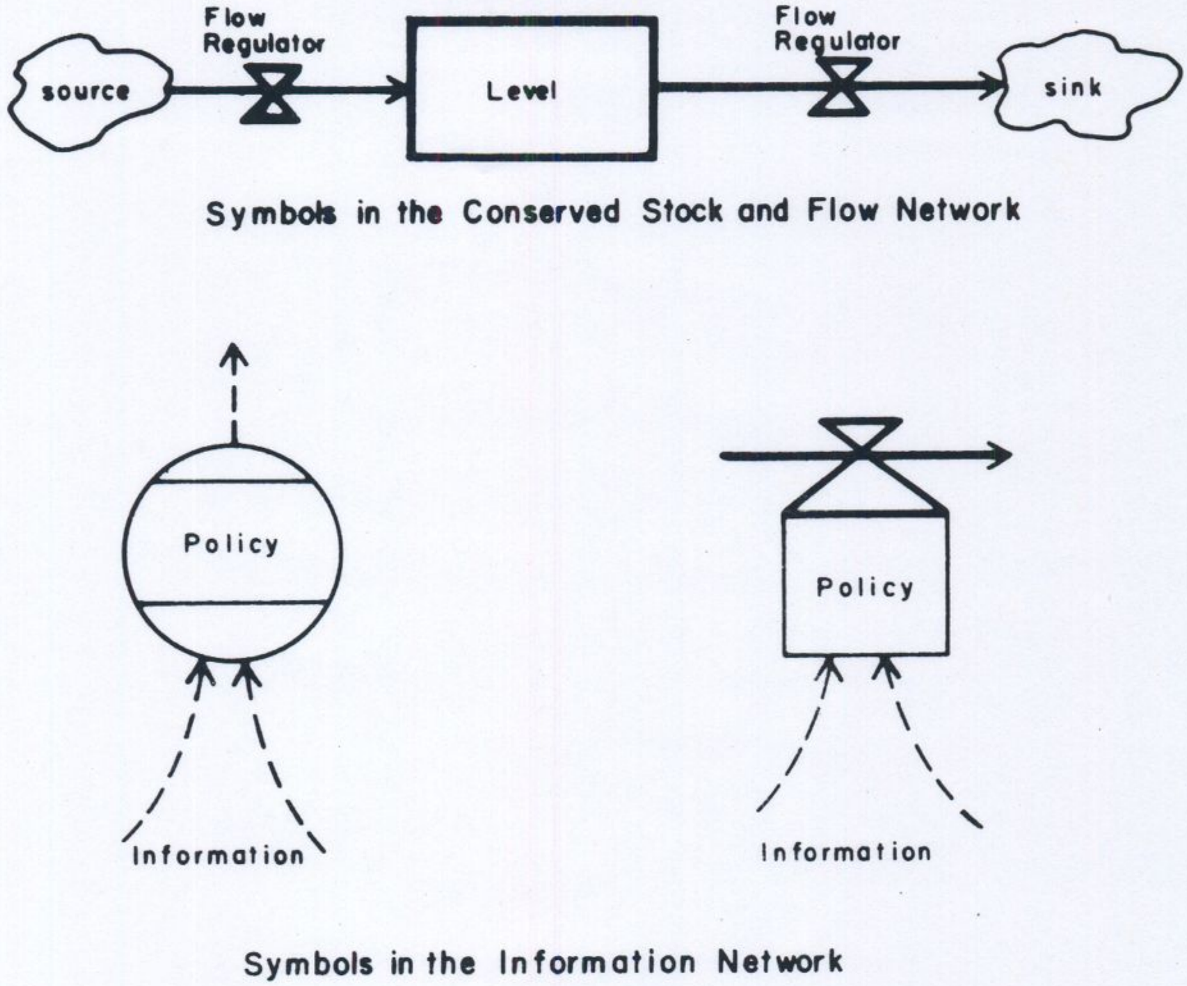

Figure 4. Building Blocks of the Policy Structure Diagram

posed probe the limitations of human decision making. These limitations should be reflected in the structure of the information network. For example, we can expect, on grounds of personal experience and more philosophical arguments such as those advanced by the Carnegie school (10), (11), that human decision makers necessarily take a simplified view of the system in which they operate. (See also Morecroft (12) for an interpretation of a system dynamics model from a Carnegie perspective). They cannot be aware of all activity in the system; they are likely to be most familiar with activities that are geographically or organizationally close to them. They cannot process large quantities of information, and they deliberately seek simplifying algorithms that limit the information content and complexity of decision-making. By focusing on human decision-making processes, policy structure diagrams enable us to 'compose' the information network with a full awareness of the likely limitations on network complexity. Some connections will be less likely than others. Certain combinations of information will be unlikely to be brought together in a single policy due to difficulty of combining them in a consistent way that can support a judgment. In short, we can impose constraints on the information network that should improve the quality of model conceptualization.

CASE EXAMPLE – CONCEPTUALIZATION OF MODEL TO STUDY MARKETING STRATEGY

Introduction to Case

To illustrate the use of subsystem and policy structure diagrams, we present an example taken from a corporate project studying the marketing strategy of a company in the data-processing and communications field. During the project wide use was made of the new diagraming methods. The diagrams served as the primary vehicle for conceptualization. They provided a fluid framework to guide the detailed stage of equation formulation. In conjunction with documented listings, they also played the role of a visual aid for explaining the model to members of the company. Finally, they served to coordinate the activities of the several people working on the project, particularly during the model-testing stage.

Figure 5 shows the subsystem diagram that defines the boundary and scope of the study. The subsystem diagram emerged in round-table discussions between a senior manager in the company, the project leader (also a manager in the company) and the M.I.T. advisor. Our intention was to examine marketing strategies that would reduce competitive incursion during a time of technological changeover in the installed base of customer equipment. Broadly, we saw the need for considering the interactions between the market and the sales and service subunits. In addition we felt it would be necessary to experiment with alternative price strategies through the inclusion of a simple price subsystem, and to

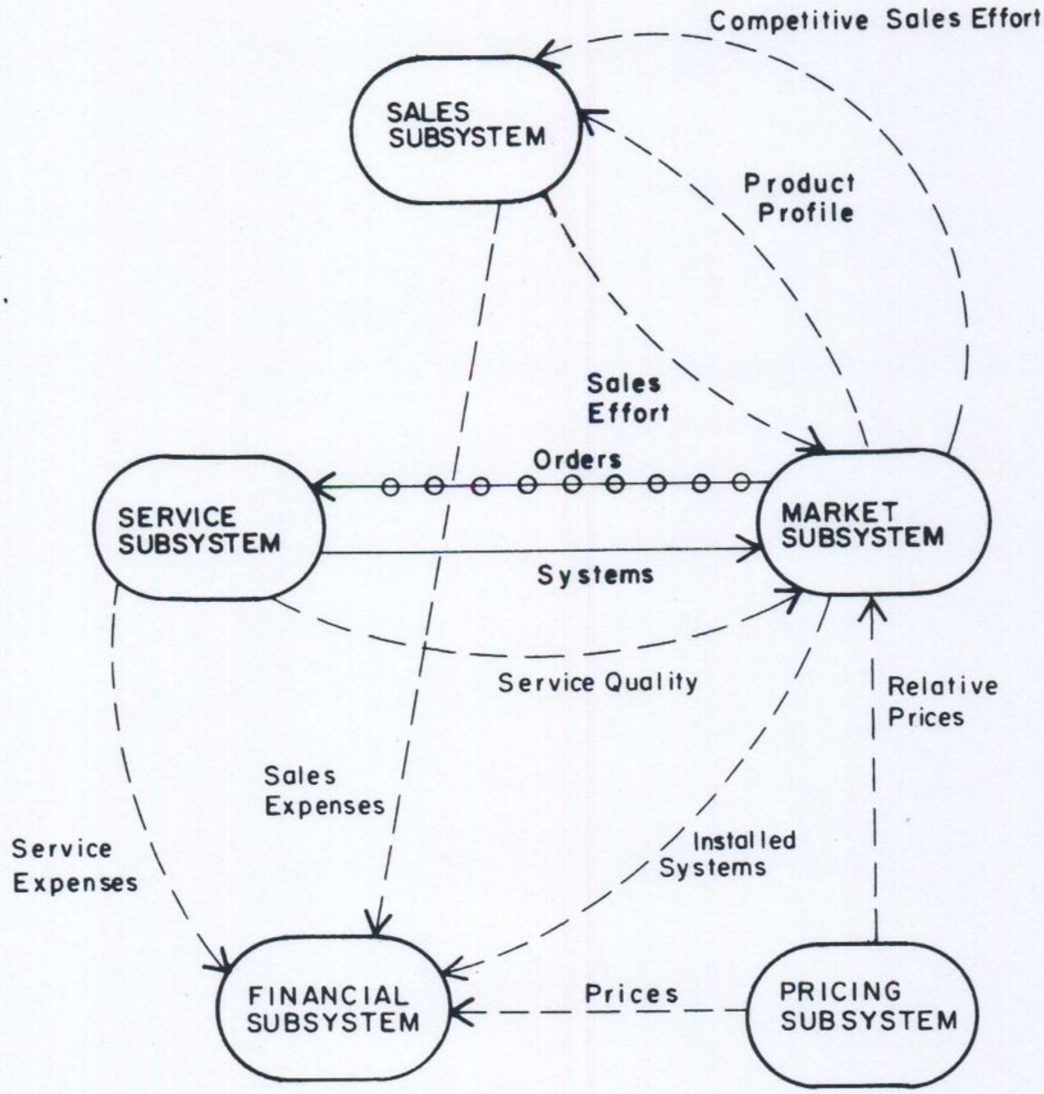

Figure 5. Subsystem Diagram of a Marketing Strategy Model

examine financial performance through the inclusion of a rudimentary financial subsystem. Figure 5 was a tentative and preliminary sketch of organizational structure as it emerged from our meetings. The linkages that are shown were by no means rigidly set and were considerably refined later in the process of creating policy structure diagrams. Nevertheless, the figure did serve as a useful starting point in the project and a communication tool for accessing the mental models of people who became involved in model development.

Policy Structure in the Market Subsystem

In the next stage of conceptualization, we considered each of the major subsystems in more detail, sketching out the internal decision-making structure using policy structure diagrams. The market, service, and sales subunits occupied the most time, as these were the areas where in-depth modeling of policy was considered most appropriate. In the paragraphs that follow we will take one particular subsystem, the market subsystem, and discuss how the policy structure diagram was created.

Figure 6 is a policy structure diagram of the market. At a glance we see a relatively simple conserved stock-and-flow network (shown in heavy black lines) regulated by a more complex information network containing a wide variety of policies. In this particular case the stock-and-flow network was created first, followed by delineations of major policies and information linkages. The order need not be fixed, however. In another situation (perhaps involving a less tangible stock-and-flow network), it might be easier to delineate policies and then trace back to conserved levels in the creation of information linkages.

The conserved stock-and-flow network depicts an installed base of unprotected old technology systems being converted either to protected new systems (the desired outcome) or to competitive systems. Overlaid on this core conversion network is the possibility for interchange between protected new systems and competitive systems, and for later additions to the level of unprotected old systems through contract expiration on protected old systems.

The information network evolved in two pieces: a relatively detailed consideration of factors affecting the project company's conversion rate and a broad sketch of factors affecting competitive conversion. For the sake of brevity we will consider only the piece dealing with the company conversion.

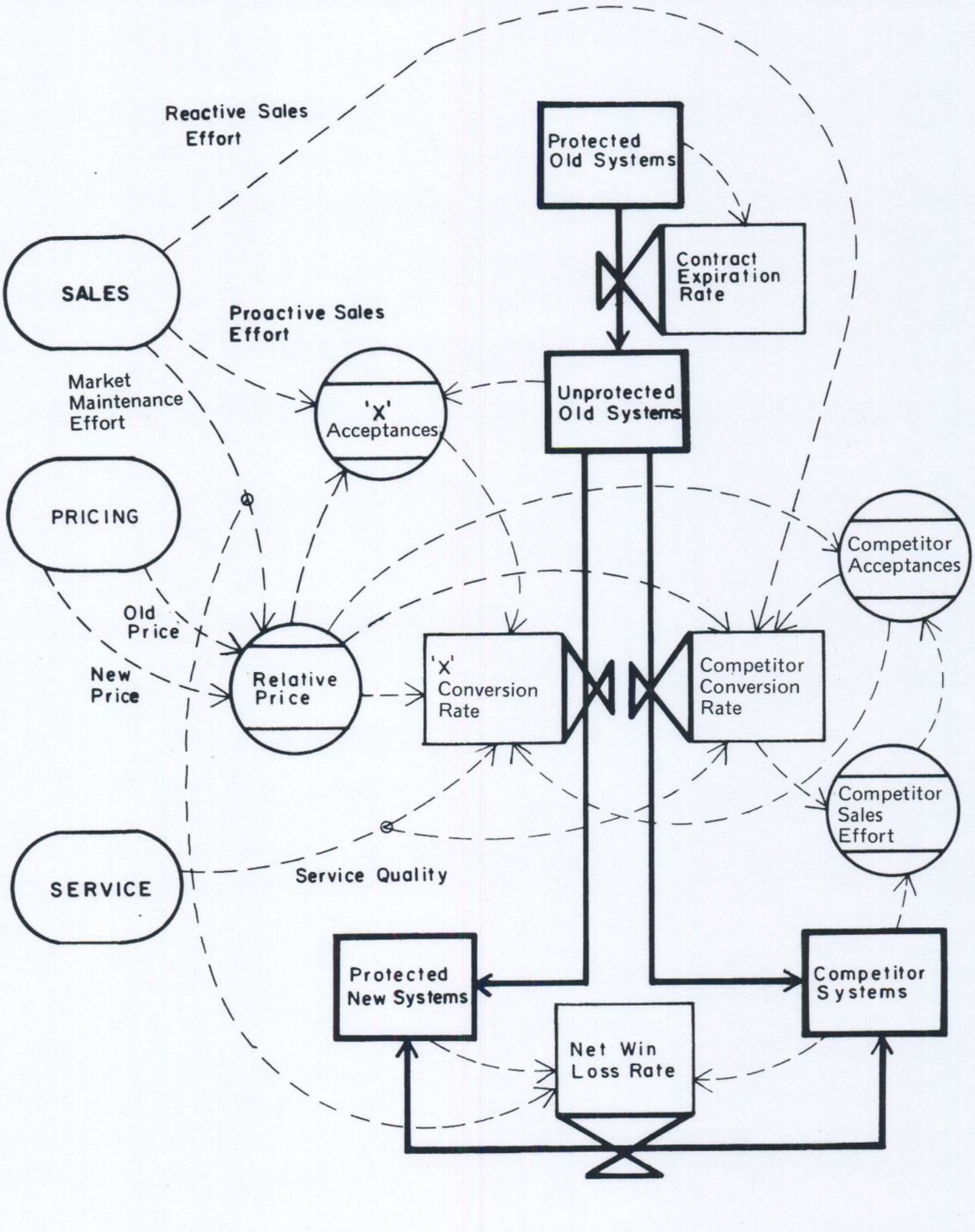

Figure 6. Policy Structure Diagram of the Market Subsystem

In the figure, the project company is referred to as Company X. Our first question, then, was what factors affect the customer's decision to convert from an old to a new X system? To answer this question, we imagined ourselves in the position of the customer (using considerable help from knowledgeable marketing people at this point). What information does the customer have? How does he make a judgement about the need to convert and whether to convert with X or the competition. Relative prices seemed a most basic consideration, so an information flow representing relative price was drawn in. But in doing this we realized that relative price was not simply a mechanical comparison of list prices. It was itself a complex judgmental process taking account of purchase versus lease options, relative prices of old to new equipment, and general price reputation. Information on relative price was therefore viewed as the output of a policy judgement on relative price whose details would be considered later. Beyond price, the customer would also need to know about the existence and desirability of the new technology in order to decide to convert. It became clear that conversion should be thought of as the second stage in a two-stage decision-making process, involving first acceptance and then conversion, where acceptance simply meant becoming aware of the new product. The X conversion policy was therefore linked to the X-acceptance policy and also to the competitor acceptance policy – recognizing that competitors could alert a customer to the existence of new technology without necessarily winning an order from the customer. The final input to the X-conversion rate was information on service quality. Since (at the time of writing) we had not given much thought to how service quality would be defined, we schematically showed an information flow directly from the service subsystem, with no intervening policy points.

At this stage the policy structure diagram had a few information links drawn in and had forced some careful thinking about the decision-making process of customers. Bear in mind that this thinking was all taking place at a level of detail far less than required for equation formulation. Nevertheless, we had learned a considerable amount about the customer conversion decision.

To conclude the analysis of customer decision making, let us briefly discuss the acceptance decision and the pricing judgment. The acceptance decision is shown schematically to depend on sales effort coming directly out of the sales subsystem, relative price (not the same relative price affecting conversion), and on the level of unprotected old systems. The pricing judgment is seen to depend straightforwardly on information about old and new prices coming from the pricing subsystem, but also on a flow of information labeled market maintenance coming from the sales subsystem. This linkage evolved out of some careful thought and discussion about the influences on customer price judgment. The complexity of pricing in the market suggested that price confusion could readily exist in the mind of the customer. Active effort on the part of the sales organization would be necessary to clarify price differentials.

Concluding Remarks on the Case

We will terminate the detailed discussion of the policy structure diagram at this point and conclude with some general observations. First, the focus on decision-making processes seems to lend some power to the generation of system linkages and to allow for easy communication to participants in the organization. Second, it should be clear that the policy structure diagram of the market is a much more concise and fluid statement of structure than the corresponding system flow diagram of the same market. The system flow diagram would likely occupy several pages and be far more difficult to communicate. Policy points such as X conversion or relative price would each be represented by many auxiliaries, constants, and table functions, greatly increasing the visual complexity of the model. Finally, the policy structure diagram was found to be an adequate diagram on which to base equation formulation. It stands in a natural hierarchical relationship above formulation. It serves as a framework in which to develop formulations, but it is not so closely tied to the formulations that there is a constant need to update the diagram to reflect small equation changes.

SUMMARY AND CONCLUSIONS

The purpose of this paper has been to take a close and critical look at the central role of causal loop diagramming in model conceptualization, and to propose workable alternative diagraming methods. The causal loop diagram was criticized on the grounds that it is a relatively weak organizing tool, neither adhering to basic structuring principles of feedback systems, nor corresponding closely to mental models, nor focusing on decision-making processes as a way of generating system linkages. A brief historical survey was included to show how the causal loop diagram has risen to its current position of prominence.

Two new diagraming tools for conceptualization were described, the subsystem diagram and the policy structure diagram, which appear to overcome many of the weaknesses of causal loop diagrams without running into the difficulties of the excess complexity usually encountered in using full system flow diagrams. The use of the conceptualizing tools was illustrated by a case example derived from a corporate marketing strategy project.

The new conceptualizing tools have been used over the past year in the introductory Industrial Dynamics course taught at the Sloan School of Management at M.I.T. Corporate systems are broken down into their component functional areas such as production control, labor procurement, pricing, marketing, etc. Each functional area is modeled as a subsystem. The decision-making processes of subsystems are studied using policy structure diagrams, then policies are combined to analyze some of the classic dynamic modes of industrial behavior: order amplification, production and labor instability, self-fulfilling forecasts, variable market growth rates, and loss of market share. Students who have taken the course have enjoyed the corporate overview that the course has provided. Others have commented favorably on the structured approach to model construction.

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Notes

1. 1. Mass-balance considerations, 2. Direct observation, 3. Accepted theory, 4. Hypothesis or assumption, 5. Statistical evidence.

2. The circular symbol is a generalization of the functional symbol used in a full system flow diagram to depict table functions or macros. Such a generalization is quite justifiable when we consider that policies are just information processors in the same way as table functions and macros.

3. The arguments developed below also serve to distinguish policy structure diagrams from 'hybrid' causal loop diagrams used by Levin, Roberts and Hirsch (8) and more recently by Richardson and Pugh (9). Hybrid causal loop diagrams clearly distinguish the stock-and-flow network from the rest of the structure, and in that respect are quite similar to policy structure diagrams. However, the process by which system linkages are developed is broadly similar to the process used in normal loop diagraming.

4. Coyle's list extension method (6) for model development is more structured, but still none of his criteria for justifying a link clearly focuses the attention of the modeler on underlying decision-making processes.