Perspectives on teaching System Dynamics.

Coupling structure and behavior, annotating simulations, and supporting Just In Time Open Learning (JITOL).

Pål I Davidsen
Department of Information Science
University of Bergen
Norway
Tel: +47 55 544134
Fax: +47 55 544108
E-mail: davidsen@ifi.uib.no

Abstract

In System Dynamics we seek to understand the relationship between the structure and the behaviour of dynamic systems. In problem solving, for instance, we must identify the structure underlying problem behaviour and find how that structure can be modified to create a more desirable systems behaviour. To enhance such an understanding, we utilize graphical techniques. Whether in print or in software, however, there has been a significant gap between our representation of structure and behaviour.

In this paper, we first present a series of ways to link structure and behaviour such that behaviour can be more easily understood on the basis of the underlying structure. These techniques are computerized using PowerSimTM.

Within the framework of an EEC research project on distance education for professionals, JITOL (Just In Time Open Learning), we have investigated how to facilitate System Dynamics distance education on electronic networks. One of the main challenges consists of finding an effective way to present the results of a simulation. Such an interpretation of simulation results is normally partitioned in accordance with the various phases of the systems development, portrayed by the simulation, and requires that references be made to the assumptions embodied in the underlying simulation model.

Consequently, the author or any other user of a model must be allowed to comment on the various phases of a specific dynamic development. Moreover, these comments must be made available to any reader of the model, ie anyone who runs the model under the conditions specified by the author or user. And these readers must be allowed to respond by adding their own comments to the same fragments of the model development.

This paper outlines a technique developed to, at runtime (ie as the model is running), link such annotations to graphs that represent simulation results, and to make such annotations available to readers at runtime when they inspect that specific simulation.

Perspectives on Teaching System Dynamics.

Coupling structure and behavior, annotating simulations, and supporting Just In Time Open Learning (JITOL).

Introduction

Ever since 1956, system dynamics has been used as an educational vehicle for management, teaching, and learning (Forrester, 1961, 1989). It has proved useful in helping us describe and understand real life problems and in the design of policies intended to solve those problems. A large number of companies within a wide variety of industries, as well as research institutes and governmental agencies, are known to apply system dynamics for strategic planning purposes, as reflected by the international System Dynamics Society, its journal, System Dynamics Review, and a variety of system dynamics conferences.

We have lately seen a shift in the use of system dynamics, from activities run by external consultants to activities based upon in-house experience. This shift has come about because practitioners realize that the most durable effects of using system dynamics arise from building and working with systems models. Consequently, there has also been a change in the focus of system dynamics towards education in a broad sense (Forrester 1986, 1990b), (Senge 1990), (Senge et al. 1991). In academic research, decision-makers and policy-designers are being studied to reveal the properties of complex, dynamic systems that cause people to make inappropriate decisions and apply sub-optimal policies (Sterman 1989), (Diehl 1992), (Kampman,1992) (Bakken 1993). For this reason, board games and computer based "management flight simulators" have been designed (Sterman 1984, 1988), (Meadows 1989), (Diehl 1992), (Kampman 1992), (Bakken 1993). Based upon models, games, and simulators and the insight obtained from these studies, learning laboratories have been established to enhance group dynamics and organizational learning, e.g. at Sloan School of Management, MIT (Graham et al. 1990), (Senge et al. 1991), at Rockefeller Institute of Public Affairs and Policies, SUNY, (Darling et al. 1990), and at London Business School (Morecroft et al. 1990). This development rests in part upon an extensive use of personal computers and work stations. The software and hardware technology, that has facilitated this widespread use of system dynamics, has undergone major improvements over the last couple of years - a trend that is expected to continue.

In view of the extensive professional use of system dynamics and its current emphasis on education (Forrester 1990a), the potential of system dynamics as a vehicle for public education is being investigated (Mandinac et. al. 1993). Several educational projects are undertaken, run by teachers, teachers colleges and universities in USA and in Europe, and books have been written specifically for educational purposes (Forrester 1968), (Goodman 1974), (Richardson et al., 1981), (Roberts et al. 1983). An information office, The Creative Learning Exchange, has been established to tell about the experiences gained from similar activities all over the USA. In Europe, the Nordic countries have led the way, coordinated by the Nordic Council of Ministers.

Structure, behavior, simulation and graphics.

In System Dynamics we seek to understand the relationship between the structure and the behavior of dynamic systems. In problem solving, for instance, we must identify the structure underlying problem behavior and find how that structure can be be modified to create a more desirable systems behavior.

This emphasis on structure vs. behavior arise from the fact that we use system dynamics to design, evaluate, and implement strategies, each consisting of a set of interrelated and robustly balanced policies (Forrester 1980) targeted at particular functional areas, e.g. the management of sales, production, inventories, procurements, financing, personell etc.. Policies constitute structure. They relate observable aspects of the system to be managed to those aspects that are under the control of management. As a result, they determine dynamic behavior.

Strategies are being implemented in the form of information systems -- a synthesis of an organization of human beings and a network of computers. Consequently, system dynamics constitutes a tool for the design, evaluation, and implementation of information systems. In this paper, we will concentrate on implementation. Although system dynamic models are often thought of as computer-based simulation models, they may be implemented in information systems as part of a cognitive structure of a single manager or one shared by several managers or even an entire organization (Senge 1990, 1991). The problem with such an implementation is its inoperationality.

Feedback analysis using embedded behavior-diagrams

That is, we are left with a static, structural understanding -- no dynamic, behavioral understanding -- of the model. More importantly, we do not have an understanding of the intimate relationship between the structure and the behavior of such models, i.e. one that allows us to;
- identify the structure underlying a certain behavior; or
- derive the behavioral consequences of the underlying model structure or any structural modification.

As pointed out in previously (Davidsen 1992), structure and behavior can be considered linked in a causal feedback relationship (Exhibit 1).

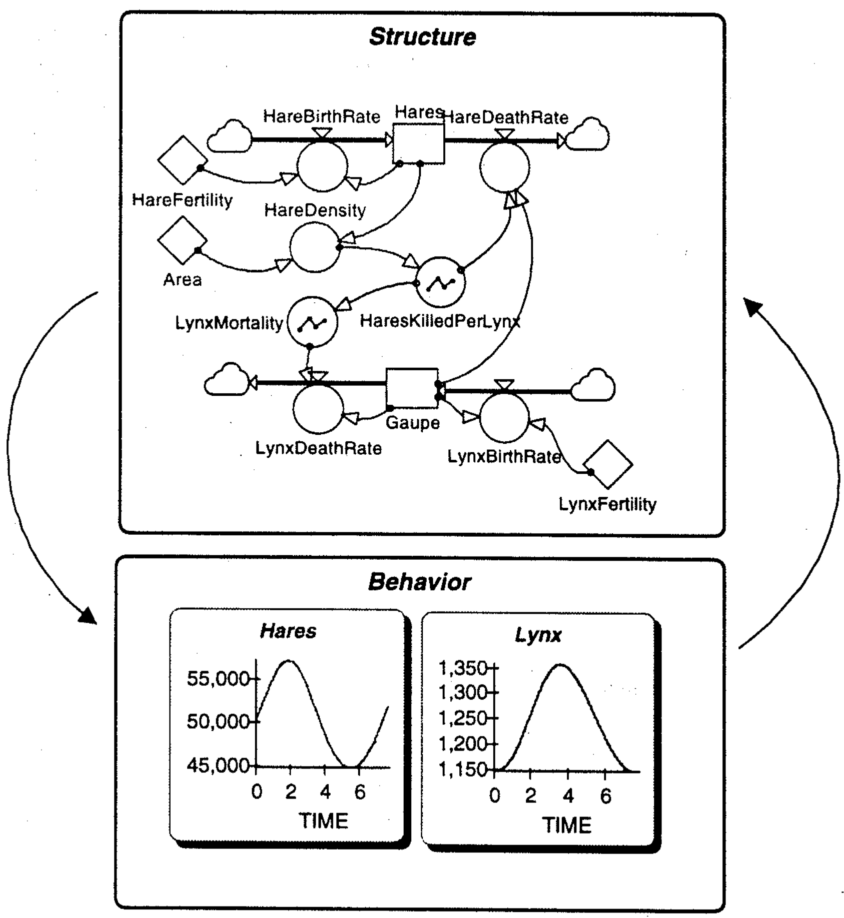

Exhibit 1: The structure-behavior feedback

On the one hand, structure determines how one state leads to the next in a sequence that constitutes model behavior. In non-linear models, on the other hand, the states in this behavior determine the relative strength of the structural components, or feedback loops, of the model. Consequently, behavior determines which of the sub-structures that dominate the resulting, subsequent behavior.

In most textbooks, and even in most software products, behavior is portrayed completely separately from the underlying structure -- typically on a different page or in a different window (pane). This separation tends to inhibit, rather than produce, associations across the cognitive boundary separating structural from behavioral thinking. System dynamics concerns the relationship between these two systems aspects and, consequently, calls for tools that combine the two. To combine structure and behavior, we need to include the results of simulations in structural diagrams, such as stock and flow or the feedback loop diagrams, and vice versa. We have chosen to distinguish between stocks and flows and utilize the corresponding diagrams even during conceptualization. Feedback-loop diagrams are merely used to summarize structural features and their behavioral consequences.

Using an extended version of Powersim™, we have experimented with several forms of combined representations of structure and behavior, some of which will be presented here. For simplicity, we illustrate our findings using the well-know predator-prey structures, portrayed in Exhibit 1.

In Exhibit 2a, the stock-and-flow diagram is combined with behavior diagrams that portray systems behavior over time. In addition, we have represented polarities, normally found in feedback-loop diagrams.

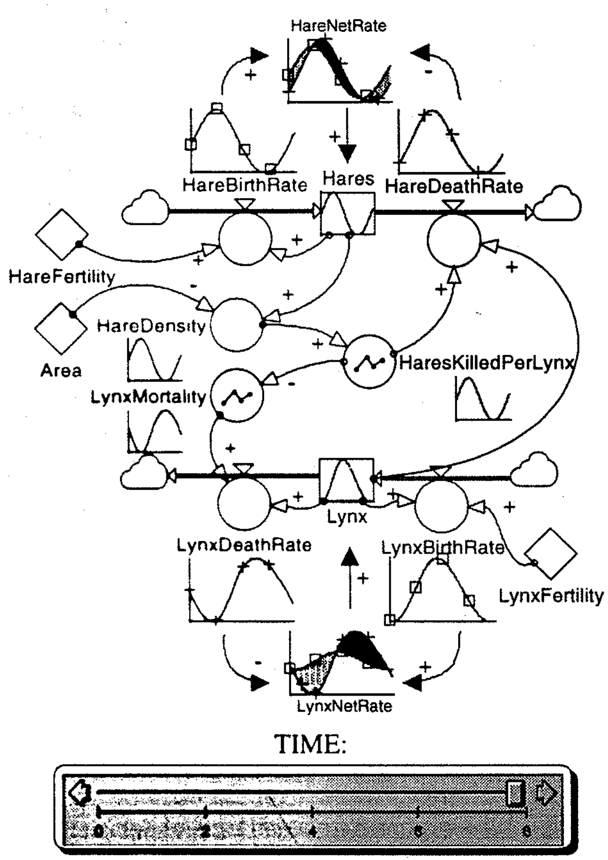

Exhibit 2a: A stock-and-flow/behavior diagram

In Exhibit 2b, the same structure is represented in a feedback-loop diagram. In Exhibit 2c, the description is reduced to a summary of the feedback structure. By carefully assigning colours to lines, markers, and fills of the time graphs so that they correspond to the colors of model components and variable names, it becomes evident how these graphs should be interpreted in view of the underlying structure.

Note the slide-bar at the bottom of Exhibit 2 a, indicating time. By utilizing this bar, students can simultaneously slide a time indicator (not shown) along the time axis in each of the behavior graphs for the purpose of comparison. Later, in connection with annotations, we will show how to utilize this slide-bare to introduce comments. Even if not shown in most of the subsequent exhibits, this slide bar would still be useful.

Implementation and application in policy design education

Although Exhibit 1 (upper part) and the various versions of Exhibit 2 may seem to share only a few properties, they all constitute a single SD model and each of them exhibits a specific aspect or layer of that model. Powersim™ allows us, by clicking a button, to show or hide various model aspects as we please. Altogether, 20 classes of elements may be swifthly selected for or de-selected from exposure. Moreover, we can assign the background color to hide subclasses of elements that altogether portray a specific portion (structural element) of a model which need not be shown.

We purposely utilize this technique for educational purposes as follows: Students are exposed to a layer of a model or to a major portion of a model, the rest of which is hidden. To prohibit access to its hidden layers or portions, the model is temporarily locked with a password. Note that, although some may be hidden, all elements of relevance to the behavior of the model, actively contribute to the generation of the simulation results. These results are being portrayed as an integral part of the stock-and-flow or feedback-loop structure diagram. This model forms a synthetic reality (microworld) with which students can experiment. The assignment is to identify the structural components remaining hidden -- a task closely resembling those of real life. For that purpose, the student is provided with a separate Powersim™- version of the visible layer/portion of the model and is expected to add the structure required to match the behavior of the synthetic reality. Such an excercise can be considered a standard system- or model-identification assignment.

In principle, however, every policy represents a structure that links the sources of significant information, through a decision making process, to the imlementation of the resulting decision. Consequently, we primarily apply this technique to train managers identify robust policies. Note that this lifts computer-based management training significantly from the operative decision making to strategic policy design and composition (Davidsen 1994a).

Moreover, the implementation of policies very often takes the form of information systems design, construction and implementation. Therefore, this technique represents a break-through in the education of information systems analysts and designers who are traditionally not trained to recognize the significance of non-linear, lagged dynamics. In fact, when tuned to our student body, synthetic realities constitutes an inspiring challenge to all kinds of students.

To summerize, note the important opportunities that this approach offers compared to the typical microworlds that take the form of "management flight simulators". In such simulators, parameter values are being set to represent short-term operative and tactical decisions made with no opportunity for the participants to investigate their consequences utilizing the workbench available to the designer of the simulator. In our case, long-term policies are being formulated and tested before implementation in a learning environment where the tools applied by the teacher to design and analyze the underlying model is made available to the student as well. To see how students may be challenged to identify such polices, refer to Exhibit 6 and the accompanying text.

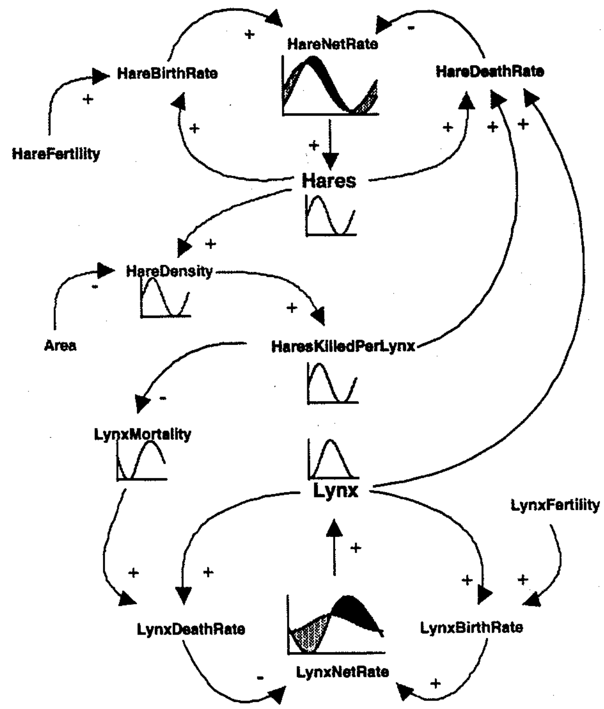

Exhibit 2 b: A feedback-loop/behavior diagram

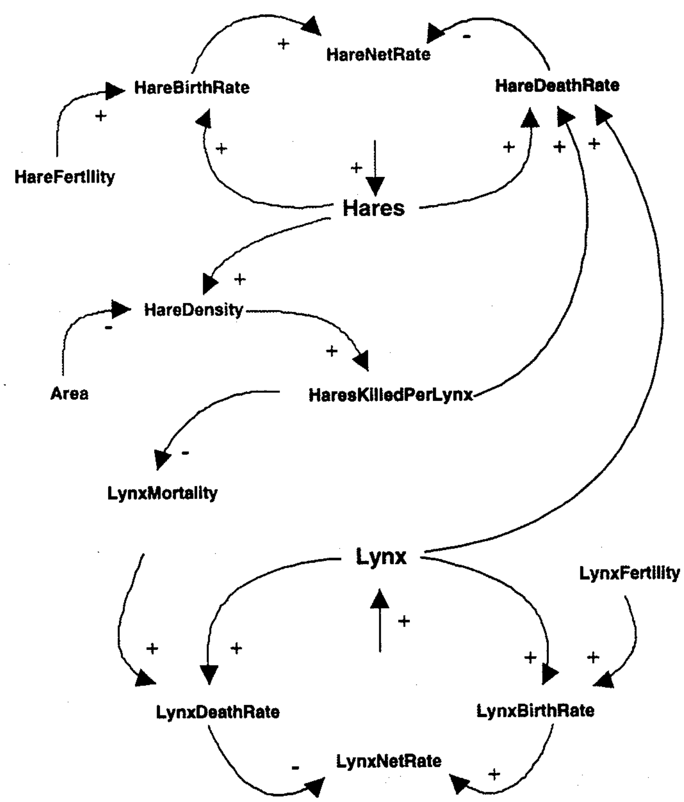

Exhibit 2 c: A feedback-loop diagram

Feedback sensitivity analysis using embedded structural scatter-diagrams.

One of the major problems when trying to understand how behavior arise from a non-linear structure and how the structure can be modified to improve behavior, is the sensitivity of structural dominance to the behavior of the model. In our example, we see how the strength of the small negative loop, associated with hare deaths is determined by the number of lynx and how the small negative loop associated with lynx deaths is determined by the availability of hares. That is, the behavior effect of each loop (population dynamics) determines the strength of the other loop (fertility and mortality, respectively) and thus shifts relative dominance of the structural loops between various phases of the development of the population feeding back to actually cause that pattern of behavior. This description clearly captures the structure/ behavior feedback portrayed in Exhibit 1.

We now focus on one segment of the model, the mortality of the lynx and its sensitivity to the number of hares killed per lynx. This relationship is a non-linear one, and in our dynamic analysis, it is typically important to recognize the general nature and the current significance of this relationship as a consequence of the state of the system (note that, at this stage, the simulation has not been completed). In this case, the non-linearity is conveniently expressed in the form of a graph (NB!) which we now introduce in the diagram (Exhibit 3) along with an indicator (vertical bar) that characterizes the current state of affairs. In this case, it is indicated that the lynx mortality is varying relatively far from its maximum and minimum. More importantly, it can be determined that only a slight increase in the availability of hares will reduce mortality. This latter remark indicates the significance of these graphs in sensitivity analyses and their contribution to qualitative dynamic analyses in general.

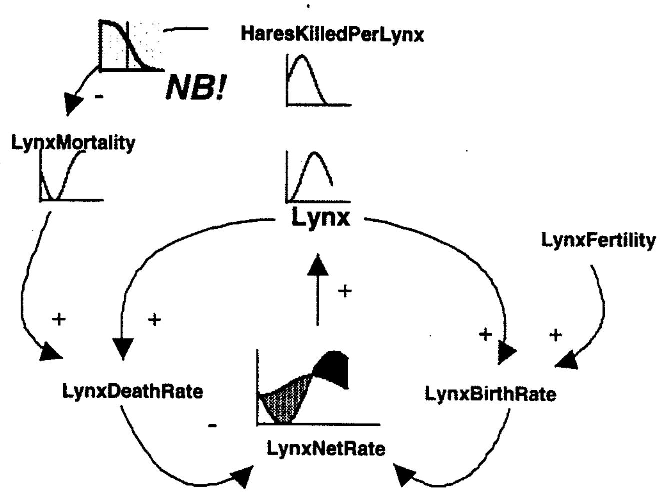

Exhibit 3: A feedback-loop/behavior diagram

Documentation of model structure and behavior through annotations in the context of JITOL (Just In Time Open Learning)

Within the EU-project JITOL, Norway contributes both in the technical, the evaluative, and the application-oriented work-packages. In the latter package, our purpose is to train educators in the use of information technologies relevant to their needs. Among the courses currently under development is one on dynamic modeling, one on computer-based learning environments for system dynamics, and one on management training simulators. This may constitute a basis for a Pan-European education of system dynamicists at graduate level in the context of the ERASMUS student exchange program (Davidsen 1994b).

In the JITOL project, we will teach professional educators to analyze, build, and utilize simulation models as a basis for interactive hyper-media productions based on peripheral technology (Davidsen 1993). The software environment, in which this education will take place, consists of three electronic books; a textbook, one of assignments, and a workbook along with a technical dictionary. They are all related in the form of hypertext. There are hyperlinks to Powersim™ models that constitute a platform of examples from which students can work. Winix™ network software is available so as to allow the student to participate in conferences or communicate directly with the advisor, including sending graphical material and simulation models as appendixes. Because the modeling process itself is so crucial, it will be possible to record annotated modeling sessions and send them on the network for consultation. Utilizing moving/picture/-icons, participants can exchange illustrative references at low transmission costs, pending efficiently transmitted source material. In this section we illustrate some of the requirements that must be satisfied to facilitate a distance education in system dynamics in the form of JITOL.

The JITOL student is typically challenged to identify a dynamic problem, to model the problem, and to suggest and test solutions to that problem (Davidsen 1993). Initially he may turn up with a problem behavior associated with the cyclical predator-prey behavior discussed in this paper.

The advisor offeres an explanation for why the system Exhibits as oscillatory behavior, illustrated in Exhibit 4. First she creates her own model and annotates the resulting simulation, either step by step during the simulation, or afterwards using slide-bar portrayed in Exhibit 2a. At carefully selected points, she pauses, inserts comments, and resumes the simulation. When the student receives the annotated version of the model, the model itself will be hidden by the advisor (using the techniques referred to previously). When the student subsequently runs the model in annotated mode, that simulation stops at the appropriate points in time and provides access to the teachers annotations.

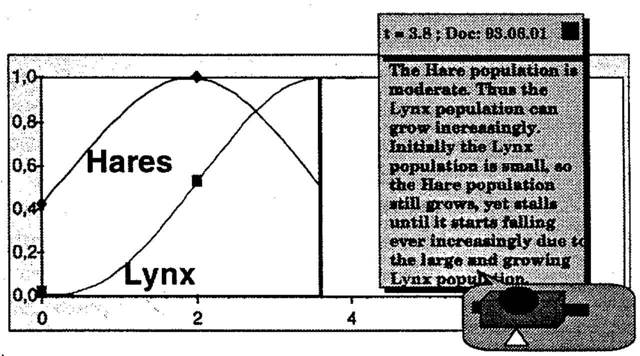

Exhibit 4: Student's explanation

The student is then challenged to create his own model of the system, i.e. a theory that explains the behavior in detail (Exhibit 5). Note that, as a part of the annotations, the advisor electronically transmits icons that refer to the underlying source material, illustrating the problem -- in this case video-footage and a textbook that will appear upon a double-click. These icons appear (disappear) at appropriate times during the simulation. The simulation will pause when such a reference appear or is activated upon a double-click. In the next section, we will return to the utilization of icons in various forms as references in a simulation-based hypermedia-production, and to their significance in long-distance education.

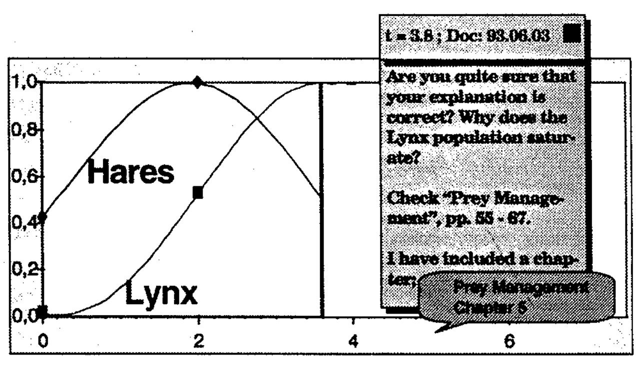

Exhibit 5: Teacher's response

Following a discussion of the fundamental relationships betwen stocks and flows, representing the state and the state-transitions of dynamic systems, the student comes up with a stock-and-flow diagram upon which the teacher typically responds with the challenge of identifying a rubost harvesting policy as illustrated in Exhibit 6.

Hyper-media access

Three kinds of technologies are associated with system dynamics modeling: the core technology encompasses the model editor and the run-time system required to simulate on the basis of any model. The auxiliary technology constitutes mathematical and graphical libraries required to analyze and display the dynamic models. Both kinds of libraries can be embedded in the model editor or run-time systems so as to support the model building, the simulation and the portrayal of results during the simulation. This is true as well for a third kind of library that provides access to or from peripheral technology, on some of which we will focus.

For the purpose of understanding complex, dynamic systems, we have traditionally utilized graphical techniques. For that purpose, as illustrated in this paper, we need to integrate a representation of behavior into one of structure - or vice versa (Davidsen 1992). Modern window management technology allows us to create embedded multi-dimensional, and colored time-plot-, vector-, and state-space-diagrams.

We face a major challenge in search for illustrations that can be applied for practical purposes across a wide variety of disciplines and over an extensive period of time: On the one hand, we need to attain a certain level of generality by utilizing abstractions. On the other hand, we want to be specific, i. e. to minimize the discrepancy between our perception of real and the way we represent (model) these issues: To facilitate model conceptualization and avoid misinterpretations, we must be concrete. It is useful to employ a series of representational forms, --some of which allow us to consider reality from a distance, and some of which bring us very close to real issues, in order to strike the requisite balance between abstraction and concreteness. System dynamics diagrams are all typically abstract. They are ideal to describe generic components, but less suited to trigger real life associations. They offer students a relatively limited expressive power by which they are expected to portray their vision of reality. To some students, such a high degree of abstraction may constitute an unsurmountable threshold.

The introduction of animation constitutes an additional dimension that may cause students to associate their model

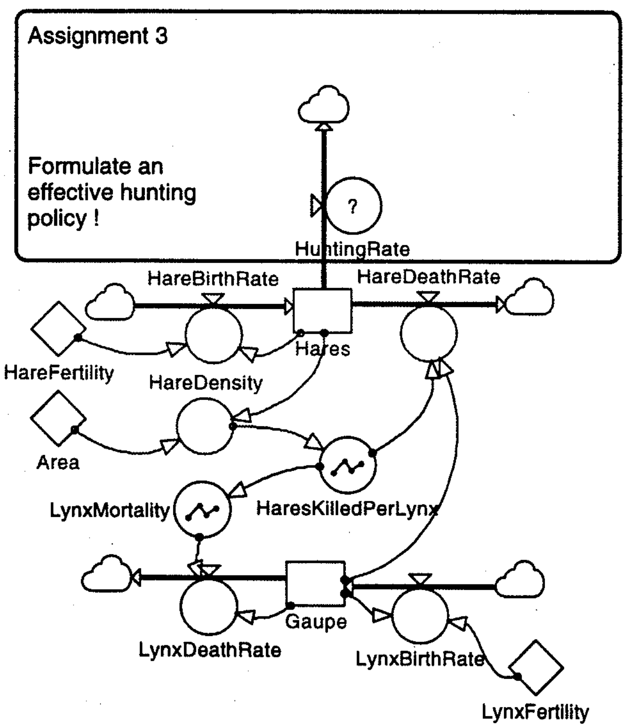

Exhibit 6: An assignment

observations with real phenomena. We operate in animation with interactive interface objects that can attain properties such as size, color, position (both absolute and relative to each other), speed, and direction of movement etc. We can make extensive use of animation to portray the relationship between structural components, their individual behavior, and their interactions. The major advantage of animation is the precise relationship that we can establish between the dynamics of a model and the corresponding animation. Moreover it can contribute significantly as overlays on interactive video-productions. On the other hand, there are two disadvantages: The creation of an animated production is the job of a highly skilled specialist and demands relatively large amounts of resources. And, though they do trigger associations, animations are seldom close enough to reality to substitute for video. Note, that though animation is inherently dynamic, few languages have been developed that describe dynamic behavior. The system dynamics language is one that we can use to provide substance to our animations.

Video-productions have become intimately integrated with computer technology in the form of interactive video. Such video productions allow the individual student to explore visual, textual and audible material that form a hyperspace. Digitization techniques facilitate the creation of p(icture)icons and m(oving) icons, icons that contain picture or film material. We can include picons/micons in the structural or behavioral presentation of models, as references to the original material, stored on peripheral technology. As an illustration of structure, picons/ micons would typically be superimposed on top of the elements of stock-and-flow or feedback diagrams (or some animated version of such diagrams). By double-clicking on the p/micons, the underlying material, that illustrates levels and rates and the relationships between them, is brought onto the screen in full size. The video material may also illustrate the typical behavior produced by selected structural components of the system in isolation. Likewise, during the simulation, p/micons may be appearing, triggered by the behavior of the model, referring to material that illustrates the behavioral mode currently Exhibited by the model or to the illustration of the dominant structure underlying current model behavior. By carefully defining the conditions for the appearance of picon/ micons, their position, and the duration of their appearance, we may integrate references to structure and behavior in a way that clearly illustrates the relationship between the two. In view of the critique raised against the symptomatic approach represented by the "flight simulators", it should be stressed that the interactive video approach thus offers an opportunity to associate the two systems aspects, not only as they are portrayed in the model, but also as they appear in reality.

By utilizing overlay technology, we can combine real life references in the form of video-footage, with traditional diagrams and animation. We can use overlay to emphasize important structural relationships that produce the dynamic behavior illustrated in a video-sequence. Or we can use the technique to animate the behavior, created by the interaction of components, appearing in the video.

Full motion video digitization with compression/decompression enable us to download, manipulate, and retrieve video in real time, using a minimum of space so that video and sound will appear as data types, stored on digital media along with textual and numerical information. The representation of all forms of information on a common platform facilitates the integration of these forms to support the illustration of dynamic systems properties. More importantly, it allows students to use consumer video recorders to document their models and to apply their own footage annotations, to link this reference material into their models at their convenience, and to combine it the way they find most illustrating. This enhances learner participation, adds to the meaning of interactiveness and opens up for new, learner-defined ways to understand complex behavior.

References

Andersen, D. F., Richardson, G. P., and Sterman, J. D.(eds.): "System Dynamics '90". Proceedings of the 1990 International Conference of the System Dynamics Society, The System Dynamics Society, MIT, 1990.
Bakken, B. E.: "Learning and transfer in Simulated Decision Environments.", Ph.D. thesis, MIT, Cambridge, Ma, 1993.
Bartha, B.Z. et al. (eds.): Computer Mediated Education of Information TEchnology Professionals and Advanced End-Users", IFIP Transactions, North-Holland Publishing Company, 1993.
Darling, T. and Richardson, G.: "A Behavioral Simulation Model of Single and Iterative Negotiations", 1990 (Andersen et. al., 1990).
Davidsen, P.I.: "Der Rütli Management Simulator -- a new concept in system dynamics based management flight simulators", The 1994 International System Dynamics Conference, Stirling 1994a.
Davidsen, P.I.: "Possibilities and challenges for system dynamics research and education in Europe ", The 1994 International System Dynamics Conference, Stirling 1994b.
Davidsen, P.I.: " System Dynamics as a Platform for educational software production", in Bartha, B.Z. et al., 1993, pp. 27 - 40.
Davidsen, P. I.: "The Structure-Behavior Diagram: Understanding the relationship between structure and behavior in complex, dynamic systems.", In Proc. 1992 Int. Conf. of the System Dynamics Society, pp. 127-136, Utrecht.
Diehl, E. W.: "Dynamic Decision Making as Influenced by Feedback.", Ph.D. thesis, MIT, Cambridge, Ma, 1992.
Forrester, J. W.: "Beyond Case Studies --Computer Models in Management Education." System Dynamics Group,1990b, D-4188, System Dynamics Group, MIT.
Forrester, J. W.: "System Dynamics as a Foundation for Pre-College Education." 1990a, D-4133, System Dynamics Group, MIT.
Forrester, J. W.: "The Beginning of System Dynamics." Banquet Talk at the System Dynamics Society Conference, Stuttgart, Germany, July 1989, D-4165, System Dynamics Group, MIT.
Forrester, J. W.: "Lessons from System Dynamics Modeling", System Dynamics Review, 1986, 3(2).
Forrester, J.W.: "System Dynamics - Future Opportunities", in Legasto, pp. 7 - 22, 1980.
Forrester, J.W.: "Principles of Systems", Wright-Allen Press, 1968.
Forrester, J. W. : "Industrial Dynamics", The MIT Press, 1961.
Goodman, M. R.: "Study Notes in System Dynamics", Wright-Allen Press, 1974.
Graham, A. K. and Senge, P. M.: "Computer-based case studies and learning laboratories projects", System Dynamics Review, 1990, 6(1).
Kampmann Chr. E.: "Feedback Complexity and Market Adjustment: An Experimental Approach.", Ph.D. thesis, MIT, Cambridge, Ma. 1992.
Kochan, T. and Useem, M. (eds.): "Transforming Organizations.", Oxford University Press, 1991.
Legasto, A.A..Jr, Forrester, J.W., Lyneis, J.M.: System Dynamics, Studies in the Management Sciences, North-Holland Publishing Company, N.Y., 1980.
Ellen Mandinach, Hugh Cline: "Classroom Dynamics: Implementing a Technology-Based learning Environment", Lawrence Erlbaum Assoc. Inc. Publishers.
Meadows, D.: "Gaming to Implement System Dynamics Models", (Milling et. al., 1989, pp. 635 - 640).
Milling, P. M. and Zahn, O. K. (eds.): "Computer Based Management of Complex Systems", Proceedings of the 1989 International Conference of the System Dynamics Society, Springer-Verlag, 1989.
Morecroft, J. D. W. , v. d. Heijden K. A. J. M.: "Modelling the Oil Producers: Capturing Oil Industry Knowledge in a Behavioral Simulation Model", 1990, (Andersen, et. al., 1990).
Richardson, G. P. and Pugh III, A. L.: "Introduction to System Dynamics Modeling with DYNAMO", The MIT Press, 1981.
Roberts, N., Andersen, D. F., Deal, R. M., Garet, M. S., Shaffer, W A.: "Introduction to Computer

Simulation: The System Dynamics Approach.", Addison-Wesley, 1983.

Senge, P. M. and Sterman J. D.: "Systems Thinking and Organizational Learning: Acting Locally and Thinking Globally in the Organization of the Future.", (Kochan et. al., 1991).

Senge, P.: "The Fifth Discipline. The Art & Practice of the Learning Organization.", Doubleday Currency, 1990.

Sterman, J. D.: "Misperception of Feedback in Dynamic Decision Making." Organizational Behavior and Human Decision Processes, June, 1989, 43(3), pp. 301 - 335.

Sterman, J. D.: "Strategy Dynamics: the Rise and Fall of People Express", D-3959-1, System Dynamics Group, Sloan School of Management, MIT, 1988.

Sterman, J. D.: "Tooling : A Model of Deadline Pressure", D-3656-2, System Dynamics Group, Sloan School of Management, MIT, 1984.