DISCUSSION: An Introductory Curriculum in System Dynamics[1]

Nancy Roberts, David Andersen, Ralph Deal, Michael Garet, William Shaffer, Tanette Nguyen and Marian Steinberg

NANCY ROBERTS is Associate Professor of Education at the Graduate School of Education, Lesley College, Cambridge, Mass. DAVID ANDERSEN is Assistant Professor of Public Administration and Public Policy at the Graduate School of Public Affairs within the Rockefeller College of Public Affairs and Policy at the State University of New York at Albany. RALPH DEAL is Professor of Chemistry at Kalamazoo College, Kalamazoo, Michigan. MICHAEL GARET is Assistant Professor of Education at the Graduate School of Education, Stanford University, Palo Alto, California. WILLIAM SHAFFER is a Senior Software Development Specialist at Data Resources, Inc., Lexington, Mass. TANETTE NGUYEN is a Budget Fellow at the New York State Division of the Budget, Albany, New York. MARIAN STEINBERG is a doctoral candidate at the Graduate School of Public Affairs within the Rockefeller College of Public Affairs and Policy at the State University of New York at Albany.

ABSTRACT

A curriculum for teaching system dynamics at an introductory level is described. The materials are designed to make instruction in system dynamics available to a wider audience than has hitherto been possible. The curriculum consists of seven self-teaching units: Basic Concepts of System Simulation; Structure of Feedback Systems; Graphing and Analyzing the Behaviour of Feedback Systems; Analyzing Less Structured Problems; Introduction to Simulation; Formulating and Analyzing Simulation Models; and Formulating More Complex Models. The packages have been field-tested at the graduate and undergraduate levels as well as at six secondary school sites in the Boston metropolitan area.

1. INTRODUCTION

With its origins in control theory and its heavy reliance upon computer-based simulations, the field of system dynamics is often thought of as an esoteric topic in management science to be taught and appreciated at the graduate level. However, many important aspects of the system dynamics approach to analyzing and solving policy-related problems do not require formal simulation. They are important skills in and of themselves and can be taught to students without extensive formal mathematical training. For example, students can learn to look for closed loop feedback-related causes to problematic behaviour with the aid of casual loop diagrams. Skills such as these have already been successfully taught at the elementary school level. Similarly, students can be taught to visualize important problems in terms of graphs of key variables plotted against time. Even the construction of formal computer-based models appears to be a resonable goal for students in non-scientific programs, since many schools currently teach computing to most students at a level sufficiently deep to allow them to write equations for a formal model.

Although many aspects of the system dynamics approach to problem solving can be taught at an introductory level, the available published cirricular material contains several gaps that prevent many schools from introducing elements of system dynamics problem solving into their curriculum. The Lesley College Curriculum Development Project has undertaken an effort to fill the gap in the available introductory curriculum materials in system dynamics. The resultant materials contain highly structured "hands-on" exercises and are intended for use in introductory undergraduate and graduate courses. However, preliminary field tests indicate that the materials may also be used by secondary-school students with some background in computing. The materials are designed to make instruction in system dynamics more widely available.

2. LESLEY COLLEGE CIRRICULUM DEVELOPMENT PROJECT

During the 1979 - 1980 academic year, Lesley College, under a grant from the U.S. Office of Education, wrote and pilot-tested an introductory curriculum in system dynamics. This curriculum consists of six self-teaching learning packages. Since then, these six learning packages have been reworked into seven units soon to be published[2]. Each unit is designed to teach a useful terminal skill in viewing and solving problems from a dynamic perspective, as well as providing a stepping stone to the next package at a higher level of skill and sophistication. The units culminate with the students constructing formal computer-based simulations. Each unit contains many "hands-on" exercises and sufficient explanatory material to allow students to master the materials either working independently, in small groups, or as a whole teacher-guided class. The units are designed to be taught by teachers who have had no previous formal training in system dynamics. Packages five, six, and seven require computer support, in a specialized system dynamic-related simulation language such as DYNAMO, or another general purpose language such as BASIC. The first four packages do not require computer support.

The packages are designed to meet several objectives. First, the packages introduce new users to the concepts of models and simulation in nontechnical vocabulary. Second, the materials provide detailed exercises in several nonquantitative aspects of model building such as casual loop diagramming, reference mode construction, and the analysis of model boundary, time frame, and purpose. Third, the units are designed to provide a detailed introduction to a simulation language (DYNAMO was used throughout the text) with vocabulary and explanatory text that is kinder and less formidable than that found in most software manuals. Finally, the materials provide several lengthy model-building exercises that take students through their first five model-building exercises in graduated steps, thereby lessening the need for detailed instructor supervision during these beginning critical attempts at constructing dynamic models. Each unit is described in more detail below.

Unit I, Basic Concepts of System Simulation, provides the students with the conceptual understanding crucial to the field of system dynamics. This package introduces the student to many different kinds of systems, shows how models are used as a method for better understanding systems, and identifies cause-and-effect relationships that can aid one in developing models. Having completed Unit I, the student will have been taught a diagrammatic tool, casual loop diagramming, for expressing the underlying casual relationships in problematic situations. This tool will be useful in helping students clarify their casual thinking.

Unit II, Structure of Feedback Systems, focuses on helping the student master the technique of casual-loop diagramming as an aid to understanding complex problems. The first part of the learning package introduces the student to the use of notation to indicate whether the change around a loop is positive or negative. The second part of Unit II teaches the student to take a written description of a problem and develop a casual-loop diagram that represents the underlying dynamics of the problem statement.

Throughout this unit, students are provided with numerous examples and exercises teaching them how to derive casual-loop diagrams from within problem descriptions.

Unit III, Graphing and Analyzing the Behaviour of Feedback Systems, introduces the student to drawing meaning out of data through the use of graphs. Further, this unit teaches the student to represent dynamic behaviour graphically, adding another problem-solving tool to that of casual-loop diagramming. As an extension of a problem centering on flu epidemics introduced in Unit II, the student is first asked to graph data from a school's records of absences caused by the flu. A series of questions and exercises based on graphs leads the student to draw inferences about epidemic behaviour such as the occurrence of a delay between infection and recovery, and relationships between the rate of infection, recovery, and the immunity of a population.

As the package continues, the student is taught to think quantitatively in preparation for building computer models. The last chapter of this unit illustrates how the use of both of these skills strengthens one's ability to understand the dynamic feedback behaviour of a system.

Unit IV, Analyzing Less-Structured Problems, integrates the skills introduced in the first three units and provides the student with a framework for problem solving. This framework is composed of four elements: perspective, time frame, problematic behaviour, and policy choice.

Perspective refers to the point of view of the concerned person. When dealing with the issues surrounding nuclear power, as an example, one's perspective on the problem is quite different if one is an environmentalist versus a nuclear power plant manager versus a homeowner paying electric bills versus a uranium mine owner.

Time frame refers to the time period of interest in studying the behaviour of a given system. In the nuclear power example, the time frame might range from 5 hours (the time after a loss-of-cooling accident during which a flow of cooling water must be maintained) to 3 years (the time a fuel rod spends in the reactor core) to 24,000 years (the half-life of plutonium –239).

Identifying the *problematic behaviour* suggests making a careful statement of exactly which aspects of the changing pattern of the system are to be isolated as undesirable. Some examples for the nuclear power problem might include accumulating expended fuel rods in nuclear waste dump sites, depletion of uranium reserves, and the behaviour of a nuclear power plant after a loss-of-cooling accident.

Finally, *policy choice* refers to the particular mode of attack that one might choose to help alleviate the problematic behaviour. For the nuclear power problem this may be to develop a breeder reactor, or to call a moratorium on the operation of nuclear plants, or to build all new plants in remote clusters, or "power parks".

Unit V, Introduction to Simulation, teaches the student the skills necessary for converting problems under study from casual-loop diagrams to computer models, and for simulating these models over time with the aid of a computer. Students are introduced to the concepts of levels and rates, then taught to develop flow diagrams, and finally to write equations quantifying the relationships within the model to the point needed to carry out computer simulations.

The students are taken through several hand simulations of simple models to develop their understanding of simulation and to clarify the computer's role in simulation. DYNAMO is introduced as a language for continuous system simulation. By the end of Unit V the student will have interacted with a computer by creating and running very simple models.

Unit VI, Formulating and Analyzing Simulation Models, presents the students with four problems that they can develop into simple computer models. These problems are: the impact on an ecosystem by the interference of people–The Kaibab Plateau; the rise and fall of an urban area–Urban Dynamics; a study of supply and demand--Hog Cycles; and a study of epidemics--Influenza.

This chapter begins by taking the student very slowly through the steps of model building and simulation: defining the problem, drawing the casual-loop diagram, drawing the flow diagram, writing the equations, running the model on the computer, and testing, analyzing, and using the model. The Kaibab Plateau problem is broken down into the smallest of steps, with each following problem being somewhat more open-ended.

This set of problems was chosen to illustrate the most common types of behaviours that arise from dynamic systems. At the completion of this learning package, the students should be able to formulate and run simple simulation models and use simulation to examine selected topics in any of their social or natural science courses.

Unit VII, Formulating More Complex Models, deepens the discussion begun in Unit VI and introduces students to some more advanced topics in model building. One chapter gives extended practice in the writing of rate equations with two additional modeling exercises presented–one dealing with the depletion of natural gas in an economy similar to that of the United States and one dealing with heroin addiction and its impact on the community. The final chapter sketches some of the more advanced topics that might be covered in a more advanced course on simulation using the system dynamics approach.

3. A SECONDARY SCHOOL PILOT PROJECT

In order to test for the "self teachability" of the materials, they were pilot tested in six high schools in the greater Boston area. The schools include a city school, suburban schools, and independent schools. The original six packages were used with students in grades 9 through 12 who came from a variety of academic backgrounds. The teachers using the learning packages were from computer science, mathematics, chemistry, physics, English and history. The materials were used in computing science courses, to introduce a new perspective in history, and to teach creative thinking and problem solving in English. In some schools the students built models in BASIC as well as DYNAMO. The initial project involved students interacting with the materials in small groups, individually, and in conjunction with teacher-assisted classes.

Both the teachers and the students involved in the pilot testing helped the author team to reach the objective of writing a set of self-teaching introductory system dynamic packages by working theough the materials, by commenting on the materials, and by editing the materials. The packages were given an extensive rewrite based upon students' and teachers' comments.

Initial feedback from the pilot study suggests that the materials are able to accomplish the project's objectives. The project's next major hurdle is showing teachers how to integrate this material into their standard curricula. Because of concern for this issue, one of the pilot teachers wrote the teacher's manual. The manual includes suggestions for using this material within a variety of structures. Imddition, the teacher's manual includes the necessary instructions for writing system dynamics models in BASIC.

4. USES OF MATERIALS AT THE UNIVERSITY LEVEL

Although usable at the secondary school level, the focus of the current seven unit curriculum is at the introductory undergraduate and graduate levels. Over the past five years, earlier versions of these materials have been used in a variety of college courses. The more complete introductory material contained in the revised material is already being used in a variety of situations as described below.

Material from the learning packages is included in several sociology courses at Boston University. It is used here to provide a structure for thinking through sociological problems.

This introductory curriculum is also one component in a new master's program, Computers in Education, at the Lesley Graduate School. The goals of this program are to provide teachers with the necesary skills and knowledge to become computer resource people in elementary– and secondary-school settings. Simulation is a use of computing that has the potential to greatly enrich the curricula in public schools at all levels.

These materials have been used to introduce system dynamics to the middle management executive development program at the Sloan School, MIT. They are seen as a gentle introduction to quantitative thinking and to the use of computing as an aid to problem solving. The original versions of these materials have been used successfully with this group of students for several years, and it is hoped the expanded materials will enhance these students' ability to learn to use system dynamics as a management tool.

These materials are currently being integrated into a one-semester course in system dynamics methods at the master's and doctoral levels in public administration at the State University of New York at Albany. The structured exercise materials are being used to supplement traditional lecture material, providing in-depth assignment materials for both group and individual work. Providing well-worked-through material in the areas of reference mode construction, casual loop structure definition, and boundary selection as well as structured first modeling assignments with free class time to deal with other topics in model use, such as implementation and validity.

Finally, the sequence of packages is being used to prepare college students for casual-loop analyses that they will present in a course on nuclear energy. The course is taught as a chemistry course for nonscience majors, most of whom are freshmen.

5. CONCLUSION

Given the results from the field-tested data preliminary indications are that the materials developed thus far are meeting the design objectives of providing an (1) introduction to system dynamics problem solving at a nontechnical level; (2) detailed exercises in nonquantitative aspects of model building such as casual-loop construction, reference mode, and boundary selection; (3) a relatively nontechnical introduction to simulation languages; and (4) graduated computer based modeling exercises for beginning students. The material appears to fill several gaps in existing published material, easing the instructional burden at both the graduate and undergraduate levels. It is hoped that the materials will make it possible to teach system dynamics problem solving to a wider audience, including students at the secondary school level.

However, two major problems will require future consideration.. first, more attention needs to be paid to how concepts of dynamic problem solving fit into nonsystems-based courses such as traditional courses in mathematics, social sciences, or the natural sciences. Second, for entire courses in system dynamics (such as those currently taught at the graduate and undergraduate levels), more thought needs to be given to how the materials fit into existing syllabi of study. For example, in addition to those developed in the units, a complete graduate course would contain such materials as units examining the behaviour of simple structures, units in model validity and implementation, and units on parameter selection and sensitivity analysis.

For courses such as these, the materials provide very structured exercises in reference mode analysis, in casual-loop diagramming, and in the construction of models up to a moderate level of complexity. Hence instructor time is freed to treat more advanced topics.

NOTES

1. An earlier version of this paper, "Teaching Dynamic Problem-Solving at the Secondary School Level: The Lesley College Curriculum Development Project," was presented at the 1980 IEEE Conference on Cybernetics and Society and appears in the proceedings of that conference.
2. Nancy Roberts et. al., *Introduction to Computer Simulation: The System Dynamics Approach.* Reading, Mass.: Addison Wesley, forthcoming, 1982.