Extending System Dynamics for Environmental Research and Management

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Abstract

System dynamics modelling is used in many disciplines to examine the various ways in which dynamic systems function. At the University of Stirling system dynamics has been used since 1978 to model environmental processes and contribute to the management of environmental problems. These two aspects of environmental research have been reinforced by new developments in computing technology and by a greater awareness of the importance of environmental problems by both politicians and lay people. At present, however, system dynamicists have remained aloof from many developments in computing technology and it will be argued that they could be failing to make a major contribution to the understanding and resolution of environmental problems.

The main thrust of this paper is to argue that system dynamics needs to be extended into a more general framework so that detailed investigations of major environmental problems can be undertaken. In particular it is suggested that system dynamicists need to develop dynamic models to interact with several areas of information technology, especially databases, quantitative methods, geographical information systems (GIS) and expert systems in order to contribute further to the understanding and management of environmental problems. This argument is illustrated with a description of a prototype, integrated and general environmental research and management system (GERMS) developed explicitly to address the problem of modelling and managing water quality in the Forth estuary, Scotland. Some of the results of this research and its implications for environmental management are discussed. It is suggested that further developments along these lines could be made to ensure that system dynamicists make an even greater contribution to try and resolve many of the environmental problems which surround us.

Extending System Dynamics for Environmental Research and Manageme~~t

(1) INTRODUCTION

Environmental Science was established at the University of Stirling in 1978 and included computer simulation modelling of environmental systems from its inception. The Department's main focus is to investigate the processes operating on or near the earth's surface which contribute to environmental change. These processes range from purely physico-ecological forces through to important socio-economic factors which have a major impact on the Earth and vice versa (Bennett and Chorley, 1978). One unintended result of these socio-economic processes is to cause many of the environmental problems which are reported daily in the mass media. These problems include desertification, enhanced greenhouse warming, persistent pollution including acid rain, the breakdown of the ozone sphere and radio-nucllieds distribution in the air, water and terrestrial ecosystems. These topics along with many others are all part of the environmental material covered in the media and in more depth by environmental scientists. Naturally some aspects of this research feedback into the undergraduate and postgraduate courses in the Department. In several cases the use of system dynamics modelling is used to ensure that the students have a good grasp of the specific processes involved in, as well as the implications of managing, complex environmental systems. Despite these developments in research and teaching in environmental science it is clear that system dynamicists have, by and large, remained aloof from developments in other areas of information technology as applied to environmental issues. In this paper it will be argued that there is an urgent need for system dynamicists to interact with other areas of information technology so that the full potential of system dynamics models can be exploited to help both our understanding of environmental problems and their subsequent management.

This paper develops this theme by briefly outlining the various ways in which computing is use~ in environmental science and stresses the roles, actual or potential, that system dynamics can play i~ ~s initiative. In particular the need to integrate system dynamics models with databases, including sophisticated geographical information systems (GIS), quantitative methods and expert systems is noted. This is then followed by a description of a general environmental research and management system (GERMS) developed and used to help examine the problem of improving water quality in the Forth estuary, Scotland. Finally, some of the new directions needed in system dynamics are discussed so that the integration of system dynamics models with more recent developments in information technology can take place. It is anticipated that such developments could play an influential part in the on-going debate into environmental policies at a variety of spatio-temporal scales.

(2) COMPUTING AND SYSTEM DYNAMICS IN ENVIRONMENTAL SCIENCE AND MANAGEMENT

Computing is used in many areas of environmental science and management. Generally, the use of computers in environmental science and management can be justified if one or more of the following six conditions are met. First, if large amounts of data or information have to be recorded and stored as part of a databank. Next, if a large amount of calculations have to be performed on a data set. Third, if reference material is required on a specific environmental problem then access to bibliographic material stored on CD-ROMs, or in other forms, can be made from a personal computer or a computer terminal. Fourth, if, for example, various forms of computer assisted learning are required for instruction in sophisticated Geographical Information System (GIS) packages (Langford, 1991) then computers can be used to help the educational and instructional processes. Fifth, if the environmental problem cannot be analyzed in the field or laboratory then experiments and scenarios on these systems can be undertaken by using computer simulation modelling. Simulation languages such as Stella, Dynamo, Dysmap2 or other packages on either Apple Macs or IBM personal computers or compatibles are often used. Finally, when the results of the research are to be published then use of desktop facilities incl~~ng wordprocessing, spreadsheet and graphical packages are usually used.

As part of the widespread use of computers in environmental science and management, system dynamics has been used in a variety of studies. Some of these studies include global modelling including calls for sustainable development; general models of economic long-waves; urban and regional studies; resource use including non-renewable resources such as coal, oil or natural gas and potentially renewable resources such as forestry (Bruenig et al, 1986); methodological studies into the use of systems (Forrester, 1968) and the study of chaotic dynamics (Mosekilde and Larsen, 1988). Clearly, many of the issues addressed by system dynamicists are intimately related to environmental science and management. Yet it will be argued that if the full potential of this specific approach to system modelling is to be captured then it is essential that we integrate our modelling endeavours with other approaches used in information technology. In short we should abandon our self-inflicted policy of splendid isolation in the development of system dynamics and integrate our simulation practices with other complementary methods. In particular, system dynamic modellers should attempt to integrate our models with databases, especially GIS, quantitative techniques and expert systems if we are to contribute to an understanding of several real world environmental problems and contribute to the formulation of policies which will be designed to manage or solve these major environmental concerns.

System dynamics is one aspect of computing applications that have been used in environmental investigations. Unfortunately, the potential role of system dynamics has not been integrated with other aspects of information technology applicable to the type of environmental problems we address. System dynamics has been mainly concerned with temporal change and its application to real environmental policy making has been limited in part by its failure to examine spatial aspects of specific environmental problems. In the rest of this section it will be argued that there is an enormous potential for system dynamics in the area of environmental research and policy making.

A) System dynamics and Data bases.

There is an increasing tendency to develop data bases for environmental observations and information. The flat data bases of the 1970's have given way to more sophisticated relational database use. The latter, such as ORACLE, are accessed by specialised languages such as SQL (Structured Query Language) to manipulate the relevant data. Some of this data can then be stored into a tabular database or spreadsheet (such as EXCEL or LOTUS 123) so that the output of a system dynamic model can be compared with the relevant actual data. As is well known in system dynamic modelling the data requirements are not too large. Generally a set of data to specify the initial conditions, some constants and a set of parameters set up as table functions are all the data requirements for many sophisticated models.

The data sets for calibrating and subsequently independently testing the models can of course be large. For example one only has to examine the types of data for a disaggregated demographic model of China to realise that the data for validating a model can run into several billions of cases (Qifan Wang et al, 1987). At this point there is a need to develop robust methods for both parameter sensitivity tests and the optimisation of equations. Some of these methodological problems have been discussed in the system dynamics literature but not resolved (Forrester 1983; Moffatt 1983; Sterman 1983); the technical problem of optimisation of functions has been incorporated in some recent simulation languages such as SB Model Maker. Generally, however, system dynamicists have been reluctant to make a major contribution to these problems.

B) System dynamics and Geographical Information Systems (GIS)

One of the recent developments in environmental science is the use of specialised databases and software called geographical information systems (GIS). Unlike ordinary relational data bases these GISs attempt to portray the data on relative or absolute locational co-ordinate systems (Maguire et al, 1992). In a GIS, the data is referenced in a manner which will allow retrieval, analysis and display on spatial criteria. The portrayal of data in a geographical format has been welcomed and used by many environmental scientists, consultants and policy makers (Devonport, Riley and Ringrose, 19 Davidson, 1992).

The use of GIS in environmental science and modelling is quite new and rapidly expanding. Yet the concept of using several layers of mapped data to highlight spatial association is not new but was developed into a rudimentary GIS by Tomlins' pioneering Ph D thesis. From this early idea an entire GIS industry has emerged. The United Nations, for example, are using the raster based Idrisi GIS developed in the USA by Eastman et al ; and numerous government public and private environmental organisations are using large GIS manufacturing such as ESRI ARCINFO and TYDAC SPANS as well as LASERSCAN around the globe. Despite the methodological sophistication of GISs they all attempt to portray the spatial association of sets of data as tables, or more often as a map or series of maps.

There are two classic ways in which GISs are used in environmental science. The first is to portray several layers of environmental information such as soil cover, vegetation types, water quality and distance from the market and then attempt to determine the degree of spatial association between the data sets so, for example, the factors affecting the siting of fish ponds in the tropics can be undertaken. Alternatively, GISs are used to show three dimensional digital terrain models of a specific area such as forestry on Ardanoch Mor or the possible impact of mining on the local environment. These two complementary approaches to environmental investigations are often little more than empirical descriptive devices; rarely has dynamic process modelling been used to give us a four dimensional model of environmental systems. It is, however, clear that there is a need to introduce a temporal dimension into GIS. Clearly, the use of system dynamics to model environmental changes generated by environmental processes has been achieved in some studies (De Roo, 1991). It is of great importance from both a scientific and environmental management perspective that further progress is made in integrating a dynamic process model capable of indicating changes in the environment with a GIS to produce spatial patterns.

C) System Dynamics and Quantitative Methods

One of the early problems in applying system dynamics to real world problems was the failure to use conventional quantitative techniques. In the pioneering work of Forrester, for example, the models of urban dynamics and world dynamics were not subjected to the hazards of empirical refutation. The work on Lowell dynamics did attempt to show simulated patterns similar to the empirical data but in many cases careful testing of the simulated data with the actual real world data was either ignored or underscored as being of limited importance. Similarly, the attempts to model the biosphere still require further empirical research and, in many cases, further sectoral dissagregeation before they will influence environmental decision makers grappling with global environmental and economic problems associated with sustainable development. The result of this cavalier attitude to quantitative methods resulted in some researchers suggesting why few people took the early system dynamics work seriously (Naylor and Finger, 1971; Nordhaus, 1973; Madden and Moffatt, 1979).

There have, of course, been some developments in the use of quantitative methods as applied to system dynamic modelling. In 1983 Sterman suggested the use of user-defined macros for determining several relevant statistical techniques such as the root mean square percent error for testing model predictions with the relevant data (Sterman, 1983). More recently, Quifan Wang et al have suggested a set of methods both for the analysis of parameter sensitivity tests and comparing the simulated data with historical data (Qifan Wang et al, 1987). Whilst some have argued that these tests are not the only way that users of system dynamic models gain some confidence in the model it is clear that the significant lack of such quantitative tests has seriously diminished the potential size of the users of the system dynamic approach to modelling environmental and other systems. With the relative ease in which output from a system dynamics simulation model can be downloaded to a quantitative package, such

MINITAB, SPSS or SYSTAT, the reason for failing to use statistical methods for the normal procedures of testing models can no longer be ignored by system dynamicists.

D) System Dynamics and Expert Systems

Many of the problems confronting scientists and decision makers are complex. The acidification or the eutrophication of lakes are two of the myriad of environmental problems which are calling out for urgent attention. In Australia's Murray Darling river basin, for example, the eutrophication of the water is a major environmental and socio-economic problem. Similarly, the attempts to manage rangelands in Tropical and Mediterranean climates has resulted in land degradation and in some cases desertification in sensitive environments. In these and other examples of environmental problems there is a need to develop expert systems for both scientific understanding of the system and to act as an aid for subsequent environmental management and policy making.

An expert system can be defined as a computer program that embodies the expertise of one or more experts in some domain and applies this knowledge to make useful inferences for the user of the system and communicates the results and underlying logic in a natural language. Like system dynamics, and unlike most other applications of computing to environmental science, an expert system is able to capture qualitative knowledge about the system of interest such as water or land management and to justify the advice it offers in a natural, as distinct from a programming, language. Several expert systems are being developed for environmental research and this area of research promises to act as a well informed and responsive tool for aiding environmental decision making.

Many of the early expert systems used in environmental management have been developed to try and codify essentially qualitative assessments by experts in order to have a rational way of managing complex environmental systems. In the North Australian Savannas, for example, an expert system has been developed to capture the expertise in managing fires in Kakadu National Park (Davis and Nanninga, 1985). Similarly, in South Africa O'Keefe et al have developed an expert system for river conservation. The purpose of this system is described by its designers as an automated semi-numerical model for the assessment of conservation status in South African rivers. Conservation status is defined as 'a measure of the relative importance of the river for conservation and the extent to which it has been disturbed from its natural state' (O'Keefe at al, 1986; 1987). These early expert systems allow the user to interrogate the data in its database in order to discover the possible consequences of a particular course of action. It should be noted that expert systems are often dealing with qualitative data and expert opinions i.e. soft rather than hard data (Checkland, 1994; Moffatt, 1991). Nevertheless, some research has indicated that expert systems can actually outperform other types of quantitative models and some human expertise.

This brief examination of the ways in which system dynamic modelling can be improved is not meant to suggest that we as practitioners have not addressed these problems nor does it suggest that we are unaware of these other approaches to understanding real world environmental problems. In some cases the development of system dynamic models onto multi-media platforms using Stella is state of the art work. Nevertheless, what I have intended to convey is that there are still some important areas where there is an urgent need to strengthen our approach to modelling and managing dynamic environmental systems. One innovative way of strengthening system dynamics is to develop a general environmental information system which will integrate these four aspects of contemporary computing into a new useful tool for environmental research and management. It is to this topic that attention is now directed.

(3) TOWARDS A GENERAL ENVIRONMENTAL RESEARCH AND MANAGEMENT SYSTEM (GERMS)

In many estuaries there are conflicting uses of the water resource such as fishing, conservation, industrial activity as well as water abstraction and pollution discharges. The Forth estuary is located in the central valley of Scotland and like other estuaries it is a multi-purpose resource. Its tidal limit is 2 km upstream from Stirling Bridge, whilst from 56 km seawards it becomes the Firth of Forth. The environmental problem under investigation is to examine whether or not economic incentives can be used to improve estuarine water quality rather than relying upon the current consent system of water quality regulation. This research was supported by the Economic and Social Research Council (ESRC) and the full details of this research have been presented in several papers (Moffatt et al, 1991; Hanley and Moffatt, 1993). The description of the general environmental research and management system (GERMS) which emerged from this work has not been discussed. A description of GERMS is given below.

The idea underlying the formation of a general environmental research and management system (GERMS) is illustrated in figure 1. GERMS consists of five modules, namely a suite of dynamic models; a large data base; a geographical information system; a set of quantitative techniques for assessing the models and an expert system to ensure that the user of the system is guided easily through the methods as well as being able to gain the reasoning behind any given scenario. The purpose of this system is twofold: first, to ensure that the scientific research concerning a specific environmental problem can be integrated so that reasonable simulations of the system of interest can be made; second, to ensure that this information is placed in a user friendly computer based information system so that the results of different policy options can be easily interpreted by the user when applied to a dynamic four dimensional model of the system.

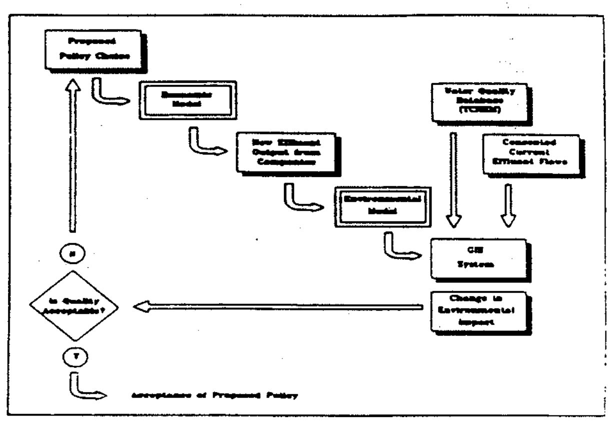

Figure 1 GERMS - A General Environmental Research and Management System

The data on water quality was supplied by the Forth River Purification Board; data on the current costs of water quality control were ascertained by a series of interviews and questionnaires of the local industrial companies and local sewage treatment works. This data consists of a large relational databank containing a relational database (ORACLE) accessed by using structured Query Language (SQL). Statistical analysis of the data was performed using MINITAB and LOTUS 123. A dynamic simulation model of water quality in the Forth estuary (FEDS) was built using system dynamics; this simulated data was then dropped into an ASCII format and transferred to a simple raster based GIS (IDRISI). Several alternative targets for reducing water pollution from point sources only were examined. Data on the cost and benefits of maintaining current water quality and the impact of improving water quality were then fed into a linear programming package (LINDO) so that the economics of improving water quality in the Forth estuary could be examined.

For any point source of water pollution in the Forth estuary FEDS simulates the movement of a particular pollutant; the output is transferred via ASCII code to the IDRISI GIS. The transfer coefficients i.e. the amount of pollution from one point source of the estuary entering in another reach are then determined in the system dynamics model before being dropped into a linear programming model to ascertain the costs and benefits of various scenarios of pollution control. Some of the results of this study are given in Table 1 where the costs of reducing pollution under the consent system and a tradeable permit (market) based system are given. It can be observed that some economic savings can be made in using tradeable permit systems but these appear only to work for a limited number of pollutants. This economic mechanism is not a panacea for overall improvement in water quality.

Target reduction %	Cost under uniform regulation £ millions	Cost under tradeable permits £ million	Least cost solution £ million
25	£7.8	£2.9	£0.69

Table 1 The consent versus the tradeable discharge permit costs for the Forth estuary

There are, however, several reservations with this study since the market based system is only capable of addressing pollution problems where trade in effluent discharge permits is common to many polluters emitting the same type of pollutant. In the Forth estuary this situation does not arise from industry so the uniform regulation approach using the consent system is the best available method of pollution control.

The results of this investigation demonstrated substantively that in limited cases the use of tradeable permits to control water pollution from point sources may be applied at lower cost than using uniform regulation procedures such as specifying maximum emission levels. There are, however, some serious limitations in relying solely upon economic incentives as the only way of protecting and improving water quality including the way of improving water quality where no other 'pollution traders' are present in the system (Hanley and Moffatt, 1993). Further research into the development of non-point sources into the estuary are being examined. From a methodological point of view this embryonic form of general environmental research and management (GERMS) system (which excluded an expert system module) appears worthy of further development.

5) Conclusion: New directions in System dynamic modelling.

This paper has reported on the ways in which computers are used in environmental science and management and stressed the potential role that system dynamics modelling can play in contributing to the wise use of the earth's resources. It has been argued that developments in several areas of computing have, by and large, been ignored by the systems dynamic community. Yet, it as been noted that in several areas of environmental research there is an untapped potential for integrated systems dynamics modelling to play. In particular the development of distributed systems models to interface with and drive GIS would appear to be an area of considerable interest and potential to the environmental community, system dynamic modellers and policy makers, both enriching our understanding and enhancing our environmental management capabilities. Similarly, with the development of data bases and quantitative methods the developments outlined above have the potential to ensure that the quantitative results of our work can be opened up to a larger community of scientists than at present. In the case of expert systems it is again possible that system dynamic model builders could develop a suite of models to ensure that these qualitative models can assist in the development of environmental strategies.

Although there are a range of environmental problems which can be addressed by systems dynamics there is need to further extend these systems so that they can easily, efficiently and sensibly address the concerns of both environmental researchers and managers. It is however important that the development of system dynamics embraces and contributes to the recent developments in environmental and computing science if we are to contribute to the development of an integrated environmental information system such as GERMS. Despite this development in environmental research it is clear that for many system dynamicists there is need to incorporate dynamic modelling more closely with other areas of information technology. In particular it has been argued that the development of distrib dynamic simulation models interconnected with a geographical information system, quantitative methods and a generic expert system is an essential aspect of the future direction we must develop for both our environmental research and contribution to environmental policy formulation. This suggestion is not, of course, the only way in which system dynamics can be applied to environmental problems but it does suggest at least one way in which the next decade of system dynamic models can be applied profitably to the serious environmental problems which surround us.

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