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DEVELOPMENT OF MODELS FOR NATURAL RESOURCES AND THEIR UTILISATION

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Introduction

The publication of Forrester's "World Dynamics" and Meadows' "Limits to Growth" has aroused considerable interest in, and not a little hostility to, the use of mathematical models to explore the complex inter-relationships between large numbers of factors in a dynamic system. The type of model used in the MIT study is not new, and has already been employed extensively in industrial and urban dynamics, but it differs radically from the data-based mathematical models to which scientists, and particularly statisticians, economists, sociologists, and environmental scientists, are accustomed. The emphasis of non-linearity of relationships between factors, and of positive and negative feedback between these factors, in an attempt to model the dynamics of a system as it really is (as opposed to the setting up of a mathematical model which minimises the constraints imposed by the mathematical assumptions themselves), is contrary to much of the formal training which such scientists have received. It is not surprising, therefore, that there should have been a strong reaction against dynamic models from scientists in the well-established disciplines. Formal mathematical models, however, frequently impose constraints and assumptions which are implicit, as opposed to explicit, in contrast to the dynamic models proposed by the MIT teams.

The reactions of non-scientists to the World Model are, perhaps, less predictable, but it is interesting that, although the model is certainly considerably more complex than the mental models which are used in decision-making in the administrative, industrial, and business world, the main criticism has been that the dynamic model is over-simplified. The criticism is almost certainly valid, but any modelling process has to begin with a model, necessarily over-simplified, which is then improved by subsequent research and development. In this respect, as the MIT teams have been the first to point out, the World Model and its various off-shoots to date are regarded as the prototypes of more effective models which can be created by further research. It is especially interesting that almost none of the controversy has been centred around the assumptions in the models themselves, although these have been made sufficiently explicit in Forrester's "World Dynamics" for anyone interested to program the model on his own computer. Admittedly, Forrester's description is in the DYNAMO language, which is, perhaps, not widely known, and is certainly not the easiest computer language in which to describe, or manipulate, such a model. Nevertheless, much of the discussion which has raged about the models would have been more valuable if it had been centred around the assumptions, and if it had led to a replacement of those assumptions by others which were held to be more reasonable.

This paper is based on the following premises:-

1. The present models of world dynamics represent only a starting point in the examination of these important issues, and considerable further research and development will be required to improve the basic assumptions, and the mathematical formulation of the models.

2. Nevertheless, at any given stage in its development, a model probably represents the best approximation that is available for describing the complex inter-relationships between the many factors operating within the system. As such, access to the model, and the conclusions which can be drawn from it, is likely to be important to those responsible for decision-making in the general field of resources, demography, capital investment, etc. A mechanism should, therefore, be provided whereby such information can be made readily available.

3. Further development of the model will require the active participation of experts concerned with the different facets, as these are the only people likely to be able to assess the validity of the basic assumptions, and the mathematical form of the relationships. It seems inevitable, therefore, that this work will be carried on by those departments and research councils at which the necessary mathematical and computer expertise is available. If a high rate of return is to be obtained from research and development devolved in this way, relatively sophisticated techniques of project planning and control will be necessary.

4. From some preliminary work on the model, it would appear that the aspects dealing with the utilisation of resources, both renewable and non-renewable, and the generation and absorption of pollution, are of particular importance, and are sensitive to small changes in the assumptions. Considerable work will, therefore, need to be undertaken within the Natural Environment Research Council to look at these important aspects of the model. Some of this work has already started at the Merlewood Research Station, and it is expected that this work will continue.

5. The MIT World Model is not the only attempt which is currently being made to simulate world systems. The simulation of bio-geochemical cycles pioneered by Morgan and Weinberg, for example, is at least as relevant to natural resources as the MIT Model, and future work will need to consider the integration of the many different approaches.

Based on these premises, this paper considers possible developments of the World Model and sub-models, and makes some positive proposals for project development.

World Model and sub-models

The present World Model considers the world as a whole, and further investigations of the assumptions and relationships at this level of complexity are required. These investigations fall into two broad categories:-

1. Methodological

There are two important aspects of the methodology of the World Model which would repay further study. Both are concerned with the need to reduce the model to its simplest form, so as to ensure that entities are not multiplied unnecessarily.

(a) Non-linearity

Although the system of modelling used in the World Model, and in Forrester's investigations of industrial and urban systems, makes a strong case for the essential non-linearity of the representation of the relationships, it is possible that the extensive feedback mechanisms incorporated in the model may themselves be sufficient to generate valid responses, and the role of the somewhat arbitrary non-linear relationships that have been introduced in the model is not at all clear. Some further investigation of this point would be worthwhile, as the

abandoning of arbitrary non-linear forms for many of the relationships would reduce the number of assumptions, and greatly simplify the interaction between the relationships.

(b) Dimensionality

Further investigation is also required of the extent to which the present model is dominated by particular relationships or variables. It may be possible to simplify the presentation of the implications by a reduction of the dimensionality of the model, and modern multivariate techniques would enable this aspect of the modelling procedure to be explored in some depth. Again, reduction of the dimensionality of the model would help to reduce the number of assumptions and simplify the model for practical use.

2. Exploration

Three models of exploring the present model, and any developments of this model, seem worth pursuing at the present time:-

(a) Sensitivity

Further investigation of the sensitivity of the model to changes in the values of the parameters is required, using the well-developed techniques of sensitivity analysis. Such investigation would focus attention on the assumptions that need further refinement, and would provide essential qualification of the results obtained from the model by the indication of the degree of uncertainty that should be attached to various estimates.

(b) Experimentation

Many of the conclusions drawn from the model so far have been arrived at by a relatively small amount of experimentation to determine the specific combinations of variables which give optimum results. Reported results have emphasised feasible combinations of variables which would at least lead to the stabilisation of quality of life and avoid dramatic population collapses through the exhaustion of resources, or the creation of massive pollution. Experimentation through evolutionary operation techniques would provide additional experience of the implications which may be derived from the model.

(c) Optimization

It may be possible to reformulate the model to obtain actual decisions, by the use of optimization techniques. The ease with which this can be done will depend, to some extent, on the importance of the non-linear terms in the model, but, even if these terms are essential, techniques of dynamic programming would provide an interesting insight into the decisions that need to be made in particular years to ensure that future decisions are not pre-empted. The present model would provide a convenient tool for experimentation and simulation of this kind.

In addition to investigation of the model of the world as a single entity, it seems likely that further development could be made in terms of sub-models. One of the weaknesses of the present model, for example, is the relatively uneven development of the separate continents or groups of nations. Many critics have, therefore, suggested that a valid model must consist of a series of linked sub-models. Each of these sub-models would refer to a distinct continent or group of countries, for which the rate of development in terms of capital investment, quality of life, etc., was approximately equal. It is doubtful if the necessary information for such sub-models is, in fact, available or obtainable.

There is, perhaps, a particular temptation to construct a United Kingdom sub-model as, through Government agencies, much of the information that would be required could be obtained. The feasibility of such a model should be explored, but it is likely that difficulties will arise because of the complex import/export feedback loops that would be necessary for natural resources and capital investment, as well as for the rather complex population changes which have taken place over recent years, and which may be envisaged in the near future. It would certainly be necessary to attempt to model the relationship of United Kingdom with Europe, and possibly also with the North American continent. Despite its conceptual attractiveness, the priority for such a model is probably fairly low, even if it is shown to be feasible.

A more attractive alternative series of sub-models would be based upon studies of the World Model as a series of systems containing broad groups of closely related variables. Inputs would be required from other sub-models, but expansion of the assumptions to include a wider range of state variables, level variables, and rates, would be possible, and the composite model would be made more acceptable to the groups of specialist interests for which it attempts to cater.

Preliminary study of the World Model suggests that at least five sub-models would be worth further investigation:-

(a) demography, including population, birth rates, death rates, and crowding ratios;

(b) natural resources and pollution, including natural resource levels and usage, pollution generation and absorption, etc;

(c) investment, including capital investment, material standard of living, agricultural investment, etc;

(d) agriculture, including food, capital investment in agriculture, etc;

(e) quality of life, including effects of food, crowding, pollution, etc. on environmental quality.

Development of the composite model, and of the proposed sub-models, would necessarily have to be carried out by the departments and research councils which have the necessary specialist knowledge. A more serious limitation may be the limited mathematical and computing expertise and facilities which are available for such work. Some of the research and development could be carried out at universities, but the nature of university grant schemes makes it desirable that the co-ordination of the total project should be undertaken by a Government department or a Research Council. Much of the information which will be necessary if the model is to be realistic will be classified information in the sense that access to the information will need to be restricted to staff covered by the Official Secrets Act, and, again, this would limit some aspects of the work to Government departments or Research Councils themselves.

Project development

The attached figure gives an outline network for the world dynamics of natural resources for the Natural Environment Research Council which is proposed for the Merlewood Research Station. This network is given as an indication of the kind of integrated planning that will be required if anything more than haphazard investigation of various aspects of the model is to be achieved. If other organisations undertake extensive work in relation to the World Model, it will also be important to see that the networks for the various projects are integrated so that the scarce resources of expertise in the appropriate sciences as well as in mathematics and computer science are effectively utilized, and so that no unplanned duplication of effort takes place.

Brief notes on the various milestones in the outline network are as follows:-

1. Reprogramming of World Model for an interactive computer system

   This has already been virtually achieved so as to provide more convenient access to the World Model than that provided by programs written in DYNAMO. The present model runs conveniently on a relatively inexpensive interactive computer system, and different versions of the forecasts can be obtained by simple changes in the parameters of the model.

2. Provision of advisory service to NERC agencies

   Using the interactive model, it will shortly be possible to provide an advisory service for any NERC agency that wishes to know the value of any variable or variables predicted by the World Model for given combinations of parameters. A fast service by telephone or telex is envisaged, or, alternatively, staff of NERC component bodies would be able to gain experience with the model by working directly on the computer system.

3. Definition of methodological projects

   Further consideration will be given to the methodological projects which are worth pursuing at the present time on the World Model. These will be drafted as outline project plans, cpmplete with preliminary networks, objectives, criteria for success, and estimates of the resources that will be required for the satisfactory completion of the project. Some of the projects will undoubtedly be suitable for universities; others will necessarily be undertaken by sections within NERC component bodies.

4. Non-linearity investigation

   This project is already in preparation, and an outline project plan will shortly be available.

5. Dimensionality investigation

   This project has also been under active consideration, and an outline project plan will shortly be available.

6. Other methodological projects

These have not yet been clearly formulated, but may be expected to have lesser priority than either 4 or 5.

7. Objectives for exploration projects

The three projects for further exploration of the World Model, as it at present exists, are closely inter-related, although considered here as separate projects. The nature of their inter-relationship, and the objectives of the separate projects, is currently under consideration.

8. Sensitivity analysis

This investigation will explore the sensitivity of the parameters at present introduced into the model.

9. EVOP study of the World Model

This investigation will use the existing World Model as a simulator for an experimental situation under evolutionary operation conditions in the search for optimum conditions on the complex response surfaces defined by the operational variables.

10. Reformulation as optimization model

When the results of the sensitivity analysis and the EVOP study have been completed, an attempt will be made to reformulate the model as a dynamic programming optimization model.

11. Definition of natural resources sub-model

Definition of those parts of the World Model which are particularly concerned with the use of natural resources, pollution generation and absorption is currently being undertaken. A project plan for the programming of this sub-model is being prepared.

12. Expanded natural resources model

An expanded natural resources model is planned, from which the inter-relationship between non-renewable and renewable resources of various kinds can be explored, and the relationship with pollution generation and absorption further investigated. The model will provide opportunities for evaluating the effectiveness of recycling of scarce natural resources, and the possible demands for such resources.

13. Input from other sub-models

Inputs from other sub-models will become available, as the work by other departments and organisations reaches fulfillment and publication.

14. Model linked with other sub-models

As other information becomes available, it should be possible to improve the natural resources sub-model by expanding the inputs from the other sub-models. In this way, the close inter-relationship between the work by the various agencies concerned can be emphasised and augmented.

15. Operational natural resources sub-model

The end product of this aspect of the project is an operational model which is intended to aid decision-making in the allocation of research resources. It is not known at present whether this model will have important implications for other aspects of administrative decisions, but as comprehensive an overview as possible of natural resources in the United Kingdom in relation to the whole world is intended.

The timescales in which the various milestones of this outline network can be achieved will necessarily depend on the resources available for the project, but the order in which the projects will be completed is roughly as indicated, and the milestones have been placed in an approximate time sequence by their positioning along the horizontal axis of the diagram. First priority has so far been given to the reprogramming of the World Model on an interactive computing system, but guidance is sought as to the priorities to be given to the other activities in the network. If this outline network is generally approved, a more detailed network will be prepared showing the activities that need to be completed in order to achieve the milestones, and the resources required for their achievement. Progress of the project will be monitored by the achievement of the various necessary activities.

It is hoped that this network of project development for one Research Council will provide some guidance as to the development of the World Model in at least one important sphere of activity. It should also give a clear indication of the work that is proposed, so that unnecessary duplication can be avoided, and so that co-operative work by other organisations can be encouraged.

Outline network for natural resources world dynamic project