systems sciences and modelling

edited by a. ruberti

trends in scientific research n° 1

d. reidel publishing company
unesco

SYSTEMS SCIENCES AND MODELLING

Edited by

A. RUBERTI
University of Rome, Italy

D. REIDEL PUBLISHING COMPANY
A MEMBER OF THE KLUWER ACADEMIC PUBLISHERS GROUP
DORDRECHT / BOSTON / LANCASTER

UNESCO, PARIS

Library of Congress Cataloging in Publication Data
Main entry under title:

Systems sciences and modelling.

Includes index.
1. System theory–Addresses, essays, lectures. 2. Mathematical models–Addresses, essays, lectures. I. Ruberti, Antonio.
Q295.S965 1984 003 84-8319
Reidel ISBN 90-277-1661-7 (hardbound)
Unesco ISBN 92-3-102138-9 (limpbound)

Published by The United Nations Educational, Scientific and Cultural Organization, 7 Place de Fontenoy, 75700 Paris, France and D. Reidel Publishing Company, P.O. Box 17, 3300 AA Dordrecht, Holland

Hardbound edition sold and distributed in the U.S.A. and Canada by Kluwer Academic Publishers, 190 Old Derby Street, Hingham, MA 02043, U.S.A.

Hardbound edition in all other countries, sold and distributed by Kluwer Academic Publishers Group, P.O. Box 322, 3300 AH Dordrecht, Holland

D. Reidel Publishing Company is a member of the Kluwer Group.

Limpbound edition sold throughout the world by Unesco, 7 Place de Fontenoy, 75700 Paris, France

Printed in The Netherlands

SYSTEMS SCIENCES AND MODELLING

Trends in Scientific Research 1

Preface

Unesco, in cooperation with the International Council of Scientific Unions (ICSU), and a number of international and national institutions, such as the International Federation of Institutes for Advanced Study, is publishing a series of monographs 'Trends in Scientific Research'. Each monograph will be complete in itself, but will be linked to the others by a central theme – that of developments at the forefront of science of special interest to humankind.

The idea is far from new. Professor P. Auger published a major work in 1957, 'Trends in Scientific Research', which played a seminal role in stimulating the development of science in many countries and served for many years as a handbook for science policy makers. Since this book was published, there has been a considerable extension of our scientific knowledge and it is no longer possible to fit all of science into one book if the various disciplines are to be treated in some depth. It was therefore decided to publish a number of separate monographs written by specialists and linked together to provide an extensive and extending image of present and future trends in science.

The monographs will be interdisciplinary in character, bringing together not only research in several disciplines but also the applied as well as the basic aspects of science, and in particular the uses of science in forecasting and in problem solving. Special attention will be paid to the use of science in the fulfilment of human needs.

The monographs are addressed to decision makers, to scientists interested in disciplines other than their own, the educated man in the street, and so on. It is intended that the series will provide interesting material that will influence young students to take up a career in the subjects treated.

Inasmuch as there will be a focus on applied aspects of the subjects treated, the monographs will also be of use in highlighting those types of scientific research most relevant to the requirements of developing countries and those fields of research and development with the greatest potential applications. Moreover, they will also try to highlight and foresee the most important aspects of the consequences on society of the introduction of new technologies.

The monographs will provide a series of interesting and stimulating publications which, it is hoped, will play an important role in shaping the development of scientific research and stimulating a greater interest in science in the world at large.

THE EDITORIAL BOARD

List of Contributors

Aoki, M., Professor, Institute of Social and Economic Research, Osaka University, Osaka, Japan.

Cohen, G., Director of the 'Centre d'Automatique et Informatique de l'Ecole Nationale Supérieure des Mines de Paris', Fontainebleau, France.

De Julio, S., Professor, Università della Calabria, Cosenza, Italy.

Gvishiani, J. M., Academician, Director of the Institute of Systems Studies, Moscow, U.S.S.R.

Guardabassi, G., Professor, Politecnico di Milano, Milan, Italy.

Rinaldi, S., Professor, Politecnico di Milano, Milan, Italy.

Ruberti, A., Professor, President of the Università di Roma, Italy.

Willems, J. C., Professor, University of Groningen, The Netherlands.

Introduction

Systems theory has grown to be a conceptually autonomous discipline over the last twenty-five years, out of the possibility of – and need for – a formalization and generalization of some advanced techniques in engineering design (particularly control engineering), which were made feasible by the introduction of computer technology.

As with most scientific disciplines, systems theory made use of several mathematical techniques, particularly in the field of differential equations and algebra, and provided a new impetus to new fields of mathematical research.

The validity of the use of the systems theoretic approach has, however, not remained confined to engineering alone, but has proved useful both in providing a refreshing unifying approach and in suggesting new methods in other disciplines such as economics, biology, the social sciences and physics.

The aim of this monograph is to outline the most promising trends of current research in the aspects of systems theory which deal with modelling and, partially, with controlling social, environmental and physical systems. In doing so, it may prove a useful tool for scientific policy makers in their decisions based on forecasts of research developments in the above fields, and for young graduates in the choice of their PhD thesis and the field of their future research. Moreover, it may be of interest to researchers in the social and physical sciences concerned with the systems theoretic point of view.

The above aim could be pursued only by using the expertise of an international team of systems theorists concerned with the application of systems theory to engineering, the social sciences, economics, environmental and physical sciences.

The level of the mathematical techniques which are used has been limited to a minimum in order to reach a wider audience, even if it has been unavoidable to use some mathematical language – mainly in the field of differential equations – in the articles on large-scale systems, dynamic economic phenomena and physics.

The first and preliminary article, written by S. De Julio and A. Ruberti, gives the basic conceptual foundations of systems theory, with particular reference to the process of building mathematical models from inputs and outputs, and of identifying a system. Moreover, it discusses critically the validity and reliability of the above quantitative techniques in dealing with large-scale social, economic and environmental systems, with a view to forecasting their behaviour and determining optimal or suboptimal control laws as inputs to their systems.

The following article by Academician J. M. Gvishiani, is of a qualitative-descriptive nature and mainly discusses the systems approach to the study of complex systems of various natures, and the solution which it may offer to multiple-factor and multiple-criteria problems. A distinction is made between formalizable and hardly-formalizable properties of systems, and the need to take into account 'human factors' in an organic unity with economic and technical factors is stressed. It also gives a rather detailed description of the "Modelling of global development" project which has been carried out since 1977 in the USSR.

A complete detailed overall mathematical model of some engineering systems, and most social, economic and environmental systems, cannot be profitably built using only a limited intellectual and/or computational power. These complex, real systems are called 'large-scale' systems. For these, either a coarser, more aggregated model is used, or the original system is decomposed into a set of interacting subsystems, of which the modelling and control is more readily feasible. Two articles are devoted to present research trends in the above areas, including their mathematical and computational aspects, as well as some engineering applications. More specifically, G. Guardabassi deals with the analysis of interconnected systems, the model of which consists of interacting submodels. The possibility of their computer simulation and their stability are discussed in a rather detailed way, taking into account the importance of these problems in the framework of Very-Large-Scale Integration (VLSI) technology for digital information processing. G. Cohen deals with designing optimal control of large-scale systems, via ad-hoc, or standard optimization techniques. Two methods of design are specifically described, the decomposition-coordination method and the decentralized control method. Reference is made to a particular type of large-scale system, namely power and water supply networks.

The article by S. Rinaldi deals with present trends of research in environmental sciences and the role played by systems sciences in simulating, planning, forecasting and managing water and land resources, air pollution, water pollution, ecological system and renewable resources.

Recent utilization of systems and control theoretic concepts and techniques in modelling economic problems in a dynamic framework are described by M. Aoki, who also gives an illustrative account of state space representations of dynamic problems drawn from time series models and policy models of international economics. He also shows how the state space method supplements other techniques common in economic theory, and enhances our ability to master complex dynamic phenomena in economic intertemporal optimization problems which would not otherwise render this feasible.

The final article, by J. C. Willems, discusses critically how a scientific discipline such as systems theory, which has crystallized out of the prescriptive aspects of certain advanced fields of engineering design, can be used in a typically descriptive process like modelling physical systems. In particular, it deals with the need for modelling physical systems with internal (state) and external variables, and with a system theoretic axiomatic basis for such models. Examples are drawn from classical thermodynamics and Hamilton mechanics.

A. RUBERTI

Contents

S. De Julio and A. Ruberti

General Methodologies in Systems Sciences and Mathematical Modelling

SCIENCE AND MODELS

Science, in all its stages, has always adopted some kind of model to interpret natural phenomena or artificial processes, so much so that the history of science could almost be said to coincide with that of models.

The main characteristics of the models built up until the present are their interpretative nature and quantitative formulation, and these are apparent in most processes of model building.

The *interpretative nature* comes from the need to know the phenomena under consideration better, and it is based on the adoption of physical laws or, more generally speaking, on theories by which these same phenomena can be explained. The so-called analogical models can also be related to this area of interpretation, having been created by discovering behavioural analogies among different phenomena, such that an already known phenomenon may be used as a model for another.

The *quantitative formulation* enables the mathematical construction of models which allow one to forecast the future evolution of a process or a phenomenon, once the initial conditions or causes, or the stimuli which are acting on it, are known. The characteristics that presently define the process of model construction may be recognized by considering recent trends in science evolution. One of the first trends was to extend quantitative analysis to any phenomenon, either physical or biological, economical or social. Another was to develop man's ability to predict and control phenomena, rather than just interpreting them. The increasing interest in the behaviour rather more than in the explanation of phenomena is partly a cause and partly a result of these two trends.[1]

These trends are naturally linked to the development of systems theory. In the context of systems theory a phenomenon (or process, or object) is considered in isolation from the 'universe' of which it is part and to which it is linked via different quantities that are classified in the following way:

– quantities which can be modified either directly or indirectly and that allow one to act on the phenomenon itself: these are defined as *input quantities* (*or inputs*) and can also be interpreted as control quantities;

– quantities which can be observed directly or indirectly: these are defined as *output quantities* (*or outputs*) and can be interpreted as controlled quantities;

– other quantities corresponding to interactions which cannot be ignored and somehow make up unchangeable inputs; they therefore usually take on the characteristics of *disturbances* because of the undesired effect which they can produce on the outputs.

The input and output quantities are associated with the corresponding time evolution. The set of all the possible input-output pairs is called an (*abstract*) *system* which is associated with the phenomenon (or process, or object) under consideration.

If we define it in this way, *the system appears to be usable as a general concept of a mathematical model* of a certain phenomenon and therefore can be potentially used with the widest range of goals and in the widest range of sectors. The generality of the definition indeed frees the system from the restrictions of particular disciplines and allows its greatest use. The interactions with the universe being based on the distinction between inputs and outputs, the definition also puts the prediction and control problems into immediate relief. As far as prediction is concerned, it is a question of finding the output corresponding to a given input. With the control, it is a question of determining the input corresponding to a desired output.

Finally, the complete *abstraction* with respect to the internal mechanisms that establish the dependencies between inputs and outputs allows the interpretative approach to be superseded and a behaviouristic approach used instead.

Apart from the width of scope of this approach, there has to be stressed the degree of arbitrariness linked to the isolation process of phenomena from the universe and to the evaluation of the interactions. In particular, the arbitrariness of the definition of inputs and outputs, i.e. of those features of the phenomenon which are held to be relevant and which are consistently linked to a specific point of view, should be noted. In any case, this has always taken place in the construction of models and the consequence is that *several models may correspond to a single phenomenon*. This is confirmation that the model can only represent partial aspects of a given phenomenon. A perfect and comprehensive model is not necessary because, even if one could be found, such a model would have the capacity of a direct understanding of the reality in its entirety [1].

Furthermore, it should be noted that the systems approach to the construction of models also brings in the directionality of links between inputs and outputs that some authors consider as an implicit use of the causality principle, on which, as is well known, positions can be quite different.

GENERAL METHODOLOGIES FOR BUILDING MATHEMATICAL MODELS

We have seen how the definition of the systems approach is based on the abstract system; it is, in fact, made up of all the possible input-output pairs that can be associated with a given phenomenon. At a high enough level of generalization, therefore, a system is a mathematical entity, since it is nothing more than a relationship between the set of all possible input functions and the set of all possible output functions. This entity can have different representations, from the explicit (a list of all the possible input-output pairs) to the implicit (via the mathematical conditions which the elements of each input-output pair must satisfy). Knowledge of the explicit representation of a system trivially resolves the prediction and control problems by picking out from the list all the pairs corresponding to a fixed input or output function respectively. It is clear that this path is hardly practicable, with the exception of very special cases. In order to resolve problems of prediction and control with implicit representation, we must use various mathematical theories and techniques, and (apart from elementary cases) make use of computers once adequate computing algorithms have been developed. It should be noted that the term mathematical model is often used for implicit representation rather than for the explicit one, even if both convey the same information, and this use of the word is therefore questionable. Nevertheless, given the fact that a list of input-output pairs is rarely available, it seems realistic to interpret the term mathematical model as *any implicit representation of an abstract system*. In this sense the connection between the use of models and the use of computers also becomes clear.

It is a fact that the use of models (as we interpret them here) requires calculations that are usually complex and/or heavy, and which therefore can never be carried out without the use of