MODELING OF COMPLEX SYSTEMS

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STATE UNIVERSITY OF NEW YORK AT BINGHAMTON
BINGHAMTON, NEW YORK

ACADEMIC PRESS New York San Francisco London 1978

A Subsidiary of Harcourt Brace Jovanovich, Publishers

ACADEMIC PRESS, INC.
111 Fifth Avenue, New York, New York 10003

United Kingdom Edition published by
ACADEMIC PRESS, INC. (LONDON) LTD.
24/28 Oval Road, London NW1

Library of Congress Cataloging in Publication Data

Vemuri, V.
Modeling of complex systems.

Includes bibliographical references.
1. System theory. I. Title. II. Title: Complex systems.
Q295.V45 003 77-77246
ISBN 0-12-716550-9

PRINTED IN THE UNITED STATES OF AMERICA

Preface

This book is written primarily for senior undergraduate students and beginning graduate students who are interested in an interdisciplinary or multidisciplinary approach to large-scale or complex problems of contemporary societal interest. Though there is a strong mathematical flavor, this work can also be used by a wide spectrum of students—those who tend to look at human society in terms of manifolds of interconnected problems rather than in terms of specific problems, such as pollution, poverty, or power. The purposes of this book are to help the student become acquainted with the language and framework of modern systems theory, to enable a student to recognize the internal structure of complex systems, and to impart to the student some working knowledge and skill in the use and methods of modeling large-scale systems; it is not meant to be a handbook.

This work was born out of the author's conviction that scientific and technical developments of the past few decades have set the stage for an era characterized by bigness—big explosions of population and pollution and in affluence and effluence. There is no denying that the ecology of the upper atmosphere, problems of land use, control and coordination of surface and air traffic, human communications, and responsiveness of a city to its citizens' complaints represent systems that are more complex than the familiar engineering and physical systems on which so many textbook models are based. These problems are characterized not only by their physical or geometrical largeness but also by a structure in which an essentially technological system is forced to operate in an environment that is constrained by elements that are behavioral or social in their nature. To grow more food for the multiplying myriads of human population, to build cities and make them habitable, to provide health and medical care services, and to perform a thousand other tasks in a complex society, systematic and scientific help is urgently needed. This book is addressed to the new breed of students interested in providing such help.

Because of the nature of large-scale problems, the methods of attacking them are necessarily different. Today, however, there is no generally recognized body of knowledge that can be called large-scale systems theory. As it stands today, the theory of large-scale or complex systems, if any such thing exists, is more a state of mind than any specific amalgam of methods or philosophies. The term large-scale itself is subject to value judgments. This relative state of ignorance (call it "uncertainty" if you wish) within large-scale systems theory has to be accepted at the outset. But since mathematics is the language of science, the author feels that sound mathematical and logical thinking must occupy an important position in any large-scale systems theory. To this end, bits of knowledge have been collected and organized to fill some of the needs outlined above. Since this is meant to be an introductory work, no attempt was made to make it a comprehensive treatise.

Since this work is addressed to a wide spectrum of students of various disciplines, a few relatively simple sections have been included for the sake of systematic argument. Teachers can skip these sections, perhaps giving them as reading assignments. An attempt has been made to explain various concepts by means of illustrative examples gathered from such varied disciplines as anthropology, ecology, economics, engineering, physics, psychology, and sociology. It is important that students, regardless of their primary interest, work through these examples and explore for themselves the similarities, analogies, and differences among systems arising from various disciplines. For the same reason, all the exercises at the end of each chapter should be worked out in full.

Suggestions for Term Projects

A term paper is a useful adjunct to the teaching of a course on modeling. Problems of contemporary interest are generally good candidates for investigation by students. It is impossible to list all such problems. However, to set a direction, a small sample is provided here.

1. *Global resource management* It is a well-known fact that the natural resources of this planet are distributed unevenly and are being consumed by the population unevenly and at an alarming rate. One can attempt to build models to predict the impact of various policies regarding the international exchange of resources on the economy and ecology of various nations.

2. *Radioactive dating* Fake paintings have inundated the art market in recent times. This problem therefore has some interest to the connoisseur of art. The authenticity of a painting can be verified by fixing the time at which it was painted using a radioactive dating technique because a radioactive substance, white lead (^{210}Pb), whose half-life is 22 years, is a pigment that was widely used by artists for many centuries. Similarly, carbon-14 dating can be used to fix the dates of artifacts of archeological interest. However, how do we go about detecting fake reproductions of more modern paintings of masters like Picasso?

3. *Spread of technological innovations* Economists, ecologists, demographers, and advertisers have long been interested in the process of how a new technological idea or innovation spreads in a society. For instance, it is useful to know how a new concept of birth control and family planning spreads through a society. This problem is analogous to other related problems such as the spread of a rumor or spread of an epidemic.

4. *Models for the detection of a disease* Compartmental type models can be used for the detection of a diseased condition. Indeed, the compartmental approach is rather widely used to study several problems in pharmacokinetics. For example, diabetes is detected via the glucose tolerance test. In this test, the glucose ingested can be regarded as an impulse (or pulse) applied to the gastrointestinal compartment, and the glucose levels in blood can be viewed as the response of the blood compartment.

5. *Determination of optimal drug regimen* Digitalis glycosides are effective therapeutic agents in the treatment of several cardiac problems. However, there is no well-defined and widely accepted method for the determination of digoxin dosage for individual patients. For example, a normal dosage would be fatal to a cardiac patient who is also suffering from a renal impairment. Similarly, patients with thyroid disease show an altered sensitivity to digoxin. Mathematical models would be extremely useful in such cases.

6. *Population planning* Several aspects of population planning are of interest from the viewpoint of term paper topics: (a) methods and policies for the harvesting of species that are in abundance, such as fish, and of species that are not in abundance such as whales; (b) methods and policies for the preservation of almost extinct species such as the Indian tiger; and (c) methods and policies for weed and pest control in agricultural ecosystems.

7. *Impact of family planning alternatives* There is a widespread belief that there is a lot to be gained via family planning. Are there any long-term effects of family planning that are not widely recognized now? For example, what is the impact of an altered age distribution on the socioeconomic life of a country?

8. *Planning of self-contained buildings and cities* Many innovative architectural ideas pertaining to the construction of "ecologically complete" buildings and/or cities have been sprouting up in recent times. For instance, what is the impact of a large building, which offers all opportunities and services required for normal living, located in the middle of a city? At an isolated spot away from all cities?

9. *Health care services* A frequent problem faced by planners is to decide whether to build a new hospital and, if so, where to build it. In which hospital should one locate expensive diagnostic equipment such as brain scanners and heart–lung machines? This is the so-called facilities location problem.

10. *Relation between complexity and stability of complex systems* It is widely believed that ecological systems with a number of interconnections are more stable. What is the true nature of this relation? Is there similar reason to believe that electrical power systems, for example, with a number of interconnected tielines, tend to be more stable and reliable?

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An Approach to the Problem

INTRODUCTION

Today, the system is one of the most widely used concepts in scientific investigations. Many different types of systems are familiar to us from everyday experience: mechanical systems such as clocks; electrical systems such as radios; industrial systems such as factories; educational systems such as universities; information processing systems such as computers; medical systems such as hospitals; and many more such as organizational systems, environmental systems, and cybernetic systems. We are thus concerned with a very general concept.

The behavior of systems is not always exemplary. Economic systems are subject to inflation, recession, and depression; biological systems are subject to disease and decay; educational systems are subject to obsolescence; ecological systems are subject to pests and pollution; and hydrosystems are subject to floods and droughts. What can be realized from this recital is that all kinds of systems are subject to external disturbances and do require care and the cost of this supervision is often an important factor in decision making.

There are several ways to improve the quality of performance of systems. One can build a new system and discard the old. This is a common phenomenon in some political systems and can also be done with simple mechanical systems. In several cases replacement is not at all a feasible solution. Examples belonging to this category abound: human bodies, environment, and so forth. An obvious alternative is to attempt to "engineer" the system, that is, steer it into the "proper" direction either by altering its structure or modifying the inputs or both. One way to do this is to observe the output of the system and make the said alterations such that this observed output is as close as possible to the desired output. As these alterations are being made, many of the systems cannot be put out of service. Furthermore, many systems do not operate well in a complete laissez-faire climate. Systematic methods of operating a system economically, efficiently, and in a manner desirable and perhaps acceptable to all concerned parties are needed. This is not always an easy decision-making problem; important organizational, technological, economic, legislative, and legal issues crop up in any discussion of a topic of such a pervasive nature. Some of these issues arising in this context will be discussed here.

1 WHAT ARE LARGE-SCALE SYSTEMS?

The concept of a system is very general. As our facilities do not permit us to investigate all kinds of systems, attention here is confined only to that class of systems that requires specialized approaches because of any one or a combination of the following reasons.

(1) The number of attributes necessary to describe or characterize a system are too many. Not all these attributes are necessarily observable. Very often these problems defy definition as to objective, philosophy, and scope. Stated differently, the structure or configuration of the system is rarely self-evident. In large systems involving, say, people, plants, computers, and communication links, there is scope for many possible configurations and selection of one out of several possibilities has far-reaching repercussions.

(2) The laws relating the properties of the attributes to the behavior of the system are generally statistical in nature. This is particularly true of the disturbances acting on a system. The class of disturbances is very broad, implying that the class of methods or controls used to compensate for the disturbances must be equally broad. For example, classical feedback control methods are quite effective in providing compensation for disturbances in the "technological" variables but they are less so for variations in market conditions, economic conditions, fluctuations due to time delays, and so forth. Restructuring of the system or its operation using mathematical programming techniques (linear programming, for instance) is often used under such circumstances.

(3) Complex systems are not static, they evolve in time. As the environment in which a system operates is not generally under the control of the observer, its influence as the system evolves in time is not apparent at the outset. Any system design must therefore take into consideration the fact that future disturbances may arise which are not present in the existing system, and the control system must itself evolve in order to respond effec-

tively to the future disturbances. Thus, large-scale systems cannot be designed as textbook exercises.

(4) The behavioral (political, social, psychological, aesthetic, etc.) element at the decision making stage contributes in no small measure to the overall quality of performance of the system. Because of this, many large-scale systems problems are characterized by a conflict of interest in the goals to be pursued.

It is important to make a clear-cut distinction between a system's being large and a theory developed for the study of large scale or complex systems. Whether a given system can be considered large or small essentially depends upon value judgment. What is considered complex from one viewpoint could be of simple structure from a different viewpoint.

As a rule, complexity in behavior arises due to a complexity of structure. Thus, a useful indicator revealing the complexity of a system can be found in the complexity of the behavior of a system. Therefore, it is useful to keep in mind that in any procedure aimed at modeling complex or large-scale systems the complexity of the real system should be reflected in the model.

The class of systems thus described is responsible for a new genre of mathematical sciences—the study and control of large-scale or complex systems. A significant practical aspect of the problem is not even a question of control; that is far too ambitious. It is a question of learning enough about a system to permit the development of a meaningful policy for operation. The general problem of operating a large system with limited resources and limited amount of time for observation, data processing, and implementation of control generates new kinds of mathematical questions that have not yet been precisely formulated and certainly not resolved.

Examples of Complex Systems

Although the methods and tools described herein are by no means limited to large-scale systems, the magnitude of time, money, effort, consequences, and significance of large-scale systems frequently require a sound systems engineering approach. For illustrative purposes two examples of large-scale, complex systems are presented here. It is important at the outset to recognize that these examples are not typical and the presentation is only sketchy in detail.

Management of Multipurpose River Valley Systems

In a very simplified sense, the problem faced is the following: if controlled, water in rivers is a valuable resource; if uncontrolled, it causes floods and droughts. Therefore, it is desirable to control the rivers and put the water to beneficial use. A classical method to accomplish this task is to choose a suitable site, build a dam, and use the water impounded for recreation, irrigation, power generation, municipal and industrial use, commercial fishing, and the like. By releasing the water from the reservoir in a controlled fashion it is also possible to control floods in the lower reaches of the river. Thus, in a first analysis it appears that everyone stands to gain by building a dam on a river.

A second look at the problem reveals that any large public project yielding multiple benefits almost always leads to conflicting interests; water resource systems are not an exception to this general rule. In managing water resources, several interests are involved because a natural water system can be altered in several ways. First, the problem of where to construct the dam arises. The task of determining the location of a public facility is not always governed by engineering considerations. It falls in the realm of public policy and the decisions, in general, are essentially political. Political decisions in turn depend upon public reactions, social values, and priorities. Since society is a collection of individuals, methods are required to aggregate individual values and preferences into social values. This is indeed an arduous task, and we do not as yet understand the dynamics of institutional decision making. This is a potentially fruitful area for further research.

Let us consider this problem from another viewpoint. Any large-scale human intervention with nature is likely to produce some side effects or spillover effects. For instance:

(1) A dam causes a decrease in the volume of water in the lower reaches of a river and often disturbs the hydrodynamic balance between the fresh river water and saline seawater. The result is that the lower reaches of the river, close to the sea, become salty. This salt water could irreversibly destroy productive irrigation lands in coastal areas.

(2) Construction of dams and regulation of impounded water is believed to have a variety of biological effects, some good and some bad. In Lake Torron, Sweden, after regulation, the spawning area of graylings was increased because in parts of the submerged area erosion had exposed suitable gravel bottom. Pike, on the other hand, spawn on a bottom covered with vegetation. Because the high-water period in regulated lakes comes later than in unregulated lakes, the water levels in lakes behind dams often fail to reach the vegetated areas in time for pike spawning. Thus, regulation benefits one species and hurts another.

(3) Nondegradable pollutants discharged into the river upstream from the dam tend to accumulate in the lake at higher and higher concentrations, causing the destruction of life therein.

Precisely because there is such a variety of effects from any action taken, the effort involved in the prior assessment of various alternatives is overwhelming. Consequently, computers are indispensable for systems analysis. Besides, there is no clear-cut way to answer some of the questions that arise at the planning stage. How can one compare various planning alternatives when some designs clearly favor one interest group? How can one develop an impartial yardstick for measuring the value or utility of a management policy? How can one assess and measure the actual benefits accrued by a flood protection policy? How can one measure the ecônomic or aesthetic values of a benefit called "recreation"? Can one build a public project of this kind with a profit motive? Whether for profit or not, how can one measure the success or failure of a project of this kind? There are two kinds of problems concealed in these questions. One concerns the judgment regarding the economic soundness of the projects and the second concerns the wise use of a natural resource. For brevity, let us focus our attention on the first problem.

In a multipurpose river valley project water allotted for irrigation often earns minimal revenues. There is no direct revenue from a flood control activity even though the indirect benefits accrued to the society are immense. From experience it was found that revenues earned from selling hydroelectric power are substantial. Therefore, it is of considerable interest to study the mechanics involved in the generation and selling of hydroelectric power that would possibly make the entire river valley project self-supporting.

The gist of the problem can be expressed succintly as a *negotiation problem* between two parties—the manager of the hydroelectric station (MHS) and the manager of a fossil fuel station (MFS), that is, a power-generating facility that uses fossil fuels such as oil or coal. The MHS wishes to maximize the revenue from his reservoir operations over a *planning horizon* by using a strategy of selling energy to MFS. However, as the primary purpose of the project is not power generation, the MHS has to follow certain regulations and guidelines for releasing the stored water:

(1) Releases such as those for power generation and irrigation earn a revenue.

(2) Releases such as those to satisfy the riparian rights of down-stream users, for fish and wild life conservation and salinity control of down-stream aquifers, do not earn a revenue, yet they are mandatory.

(3) Storage in the lake for recreational use may or may not earn any significant revenue but it is unaesthetic to let the shoreline recede during or before a vacation season.

In view of the random nature of stream flows, the amount of energy the MHS can generate is also a random quantity. Therefore, the MHS usually sells his power to MFS on a two-tiered contract agreement. The so called *firm-energy* sales represent a commitment to guarantee the delivery of such energy, while the *dump-energy* sales represent an agreement with no guarantee for its delivery. By failing to meet the *firm-energy* agreement, the MHS not only loses current revenue but also pays a penalty in terms of lost good will and therefore a loss in future earnings. Failure to deliver the contracted *dump-energy* results only in a corresponding loss of revenue and no penalty is suffered. Furthermore, the MHS should always satisfy the release rules engineered to meet emergency situations like flood control activities which usually have a top priority. Thus, the MHS is continuously faced with the problem of making optimal control policies, in near real time, that permits him to earn as much revenue as possible without violating other rules which have a higher priority. How can the MHS do this? One possible way is to base judgments on predictions made by well conceived and realistic models. For instance, it is possible to build a model to predict the precipitation in the catchment of a river by using a weather forecasting model (Fig. 1.1). Then using the so-called rainfall–runoff models one can predict the amount of water available in streams. The flood-routing models then make predictions about the quantity of water in rivers. Armed with this information, it is not difficult to estimate the amount of water that can be impounded by a dam. Some of this water is lost due to evaporation. Some of it is released to generate electricity, irrigate land, and a host of other purposes. The quantity of water available in the reservoir at any time can be estimated by representing the accumulation and discharge of water as a queuing process. Each unit quantity of water entering the reservoir can be imagined to be a person entering a queue. Each unit of water discharged for a given purpose from the reservoir can be imagined as an individual leaving the queue. Of course, most of these processes are random in nature. By appropriately designed models the entire process shown in Fig. 1.1 can be simulated on a computer. The predictions made from this model-building exercise can be subsequently used in decision making.

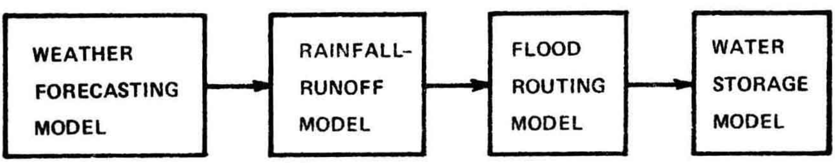

Fig. 1.1 One of many model configurations that would be useful in the management of a river valley system.

This entire process can be rendered more realistic by considering the organizational environment in which the said decisions are to be made. For brevity, only the power-generating aspect of reservoir management is considered here. To put the picture in a proper framework, it is assumed that *all*