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ESSAYS IN SOCIETAL SYSTEM DYNAMICS AND TRANSPORTATION: REPORT OF THE THIRD ANNUAL WORKSHOP IN URBAN AND REGIONAL SYSTEMS ANALYSIS

Held

November 17-19, 1980
Milwaukee, Wisconsin

David Kahn, Editor

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FINAL REPORT

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16. Abstract

This document contains the White Papers on urban-regional modeling presented at the Workshop as well as additional research papers aimed at increasing our understanding of the relationships between transportation and society. The ultimate aim is to provide analytic tools for realistically treating those relationships and providing the means to analytically explore the broad social and economic impacts of alternative transportation policies, investments and regulations.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
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yd^3	cubic yards	0.76	cubic meters	m^3
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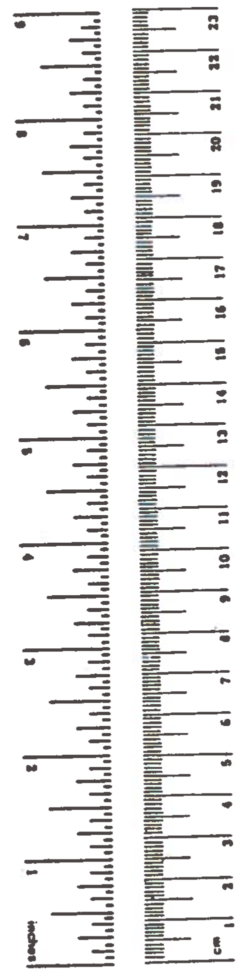

Approximate Conversions from Metric Measures

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cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
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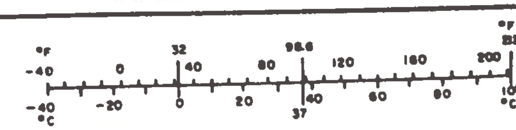

EDITORS NOTE

The papers in these Proceedings have been reproduced almost exactly as received. They contain, unhappily, a number of typographical and grammatical errors. It was felt, however, that these shortcomings do not at all detract from the content of the work, and in the interest of making this document available in as timely a fashion as possible, it has been published in its present form.

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Milwaukee, WI

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LIST OF ATTENDEES

Peter Allen
Service de Chimie Physique II
Code Postal 231
Free University of Brussels
1050 Brussels
BELGIUM
02/640.00.15 Ext. 5770

Alex Anas
Associate Professor
Northwestern University
Civil Engineering/Northwestern University
Evanston, IL 60201
312/492-7629

James T. Barry
Expert/Consultant
U.S. Department of Transportation
Research and Special Programs Administration
Washington, DC 20590
202/426-2022

Martin J. Beckmann
Department of Economics
Brown University
Providence, RI 02912
401/863-2142

Joseph Berechman
Visiting Associate Professor
University of California at Irvine
The Institute of Transportation Studies
Irvine, CA 92717
714/833-5658

David E. Boyce
Professor of Transportation and Regional Science
University of Illinois at Urbana-Champaign
Department of Civil Engineering
Urbana, IL 61801
217/333-3812

Emilio Casetti
Ohio State University
190 Oval Mall
103 Administration Building
Columbus, OH 43210
614/422-2410

Martin Clarke
School of Geography
University of Leeds
Leeds, LS2 9JT, England
0532-31751 Ext. 7273

Robert W. Crosby, DPB-10
Chief, Systems Analysis Division
U.S. Department of Transportation
Research and Special Programs Administration
Washington, DC 20590
202/426-9638

Jose B. Cruz, Jr.
Dynamic Systems
P.O. Box 423
Urbana, IL 61801
217/384-4406

Richard H. Day
Professor of Economics
University of Southern California
President, Economic Dynamics, Inc.
3650 Malibu Vista Drive
Malibu, CA 90265
203/459-1369 or 213/743-8986

Dimitrios S. Dendrinos
Associate Professor
University of Kansas
Urban Planning Program
Blake Annex #9
Lawrence, KS 66045
913/864-4184

Caroline Fisk
University of Illinois at Urbana-Champaign
Department of Civil Engineering
Urbana, IL 61801
217/333-3812

Nicholas Georgescu-Roegen
Distinguished Professor Emeritus
Vanderbilt University
Nashville, TN 37235
617/322-2871

Carvel Glenn
Director of Research
The Rice Center
9 Greenway Plaza East
Houston, TX 77046
713/965-0100

David Goette, NRM-23
Operations Research Analyst
U.S. Department of Transportation
National Highway Traffic Safety Administration
Washington, DC 20590
202/755-9384

Thomas F. Golob
Consultant
1389 Fairway Drive
Birmingham, MI 48009
313/642-2386

Abraham H. Haddad
Program Director for Systems Theory & Operations Research
National Science Foundation
Washington, DC 20550
202/357-9618

Britton Harris
Dean, School of Public and Urban Policy
University of Pennsylvania
39th and Walnut Streets
Philadelphia, PA 19104
215/243-5198

Frank L. Hassler, DTS-20
Director, Office of Systems Research and Analysis
U.S. Department of Transportation
Transportation Systems Center
Kendall Square
Cambridge, MA 02142
617/494-2563

Alan J. Horowitz
Assistant Professor
University of Wisconsin-Milwaukee
P.O. Box 784
Milwaukee, WI
414/963-4978

Arthur S. Iberall
Chief Scientist
General Technical Services, Inc.
8794 West Chester Pike
Upper Darby, PA 19082
213/HI 9-2333

Jane Jacobs
Author
69 Albany Avenue
Toronto, ONT. Canada
416/534-5329

George S. John
Central Intelligence Agency
Washington, DC 20505
703/351-3061

David Kahn, DTS-223
U.S. Department of Transportation
Transportation Systems Center
Kendall Square
Cambridge, MA 02142
617/494-2410

Alvin Keaton
Department of Philosophy
William and Mary College
Williamsburg, VA 23185

Robert Martin, DPA-32
Staff Economist
U.S. Department of Transportation
Research & Special Programs Administration
Washington, DC 20590
202/426-4228

Michael Mesarovic
Visiting Professor
School of Engineering
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139
617/253-3136

Pitu B. Mirchandani
Assistant Professor
Rensselaer Polytechnic Institute
Troy, NY 12181
518/270-6314

Lloyd J. Money
Director, Office of Systems Engineering
U.S. Department of Transportation
Research and Special Programs
Administration
1508 La Loma
Berkeley, CA 94708
415/841-2609

Norbert Oppenheim
U.S. Department of Transportation
Research and Special Programs
Administration
Washington, DC 20590

Rammohan K. Ragade
Associate Professor of Systems
Science and Mathematics
University of Louisville
University of Louisville
Systems Science Institute
Louisville, KY 40292
505/588-6482

Pauline F. Ramig
Assistant Professor of Mathematics
and Statistics
Case Western Reserve University
Department of Mathematics and
Statistics
Cleveland, OH 44106
216/368-2910

David Ramsett, DPB-25
Sensior Economist
U.S. Department of Transportation
Research and Special Programs
Administration
Washington, DC 20590
202/426-2022

Barry Richmond
Assistant Professor of Engineering
Dartmouth College
Box 8000
Hanover, NH 03755
603/643-3869

Maurice Francis Ronayne, DPB-50
Chief, Documentation & Procedures
U.S. Department of Transportation
Research and Special Programs
Administration
Washington, DC 20590
202/426-4500

Garbriel Roth
Lecturer
Economic Development Institute
of the World Bank
1818 H Street, NW
Washington, DC 20433
202/477-4422

Peter Rowe
Vice President
The Pice Center
9 Greenway Plaza East
Houston, TX 77046
713/965-0100

Barbara Segraves-Whallon
Museum of Anthropology
The University of Michigan
Ann Arbor, MI 48109

Paul B. Slater
Research Associate
Community and Organization Research
Institute
University of California
Santa Barbara, CA 93106
805/961-2548

Philip R. Smith, DPB-10
Research Fellow
U.S. Department of Transportation
Research and Special Programs
Administration
Washington, DC 20590
202/426-1688

Robert M. Thrall
Department of Mathematical Sciences
Rice University, Box 1892
Houston, TX 77001
713/527-4049

W. Tobler
Professor University of California
University of California
Department of Geography
Santa Barbara, CA 93106
805/961-3663

John W. Warfield
Professor of Management
University of Northern Iowa
School of Business
Cedar Falls, IA 50613
319/283-6008

Wing S. Wong
Scientific Systems, Inc.
Alewife Brook Parkway
Fresh Pond Shopping Mall
Cambridge, MA 02138
617/661-6364

Yacov Zahavi
President
Mobility Systems, Inc.
7304 Broxburn Ct.
Bethesda, MA 20034
301/229-7762

FOREWORD

The workshops in Urban and Regional Analysis are part of a program sponsored by the Department of Transportation to develop, test and apply improved analytical methods to assist in the policy formulation process. The need arises, on the one hand, from an increasing emphasis on understanding the social and economic effects of transportation rather than simply on the improvement of transportation itself, and on the other hand from a perception that much of what now exists in the way of methods and models is not adequate to address the subject of societal interactions. In particular, it is held that the fault lies in the weakness of the theoretical foundations of existing techniques, rather than in an insufficient development of their details. Thus a program of systems research and model development has been mounted which explores fundamentally different and potentially more powerful ways of perceiving societal systems and human behavior, highlighting their dynamic interactions with transportation.

A milestone was reached in this year's Workshop in that, for the first time, a sense of completeness of the problem definition was achieved. The fundamental limitations of conventional analysis appear now to be satisfactorily understood and, concurrently, all major lines of research that must be pursued are clear, if we are to achieve the capability of analyzing the more intractable transportation problems which involve societal interactions. Summarized below are the principal observations and recommendations of the workshop.

1. The role of the human decision process in societal analysis.

Very great success has been achieved in describing the physical world in terms of particles and fields (e.g., a mass in a gravitational field; an electron in an electromagnetic field). Human beings, to the extent we are physical, presumably can also be described in these terms. Indeed, sciences such as neurophysics and biochemistry, operating at the molecular level, are based on this concept. However, at the macro level of the complete human interacting with other humans in a society, these physical fields appear only as constraints on human physical actions, not as descriptors of social interactions. For the latter we must either acquire a far more subtle understanding of the physics of social interactions or turn to the human decision process for an explanation.

Despite the fact that people in a society do not, in fact, act as elementary particles in a field, this physical analog is nonetheless the basis for much of the existing economic, sociological and transportation analysis. The notions of economic supply and demand, with a market equilibrium are based on a physical field analog of this type. We speak of market "forces" or an "overheated" stock market, but no such forces or temperature exists in the simple sense of the physical analog. Similarly, in sociology we think of terms of peer "pressure" or the "momentum" of a political campaign. In transportation, travel is described by a "gravity" model. All these terms reveal the analogic basis of our thinking.

This is not say that physical analogs should never be used. For some questions they may be completely adequate, and therefore should be used, even as we use a geocentric model of the solar system to guide our daily lives. But as the complexity of the problems we are addressing in urban and regional system analysis increases, the simple physical analog of social behavior becomes seriously inadequate.

The most promising line of improvement in the short term lies in the use of decision theory, cognition theory and game theory to describe the human decision process analytically and then to incorporate this explicit representation in the spatial-economic models now under development.

A second approach is the development of a social physics. If it is agreed that all human action (including thought) has a physical basis, then all such actions, and the decision processes that are a part of them, should be reducible to physical laws. A complete understanding on this basis appears to be an exceedingly difficult understaking. Nonetheless, some success has already been achieved by TSC in applying constraints and conservations developed along this line. At our present state of understanding of societal systems, even qualitative insights can be of great value.

2. Nonequilibrium systems.

Much of the current thinking in the social sciences is founded on the notion that societal systems, including economic ones, are at or near equilibrium, and that the equilibrium state is the one of most interest. Analytical techniques have therefore tended strongly toward an examination of the steady state using linear mathematics. The concept of optimality is an integral part of this approach, particularly in economics, where equilibrium market systems, for example, are thought to be optimal allocators of resources.

There have been prehistoric periods where societies appear to have existed at or near an equilibrium state for as long as a thousand years. However, the western world after the industrial revolution (and now most of the world) is anything but a picture of equilibrium. To be sure, local stabilities always exist, some lasting for decades, but the overall view is one of societies in profound change, repeatedly restructuring to new technology, population and resources. These changes derive both from the internal processes of the system as well as from conditions externally imposed. The view is thus of societies lurching from one temporary stable state to another, with sometimes great differences between these states. It is interesting to note that several of the national initiatives being promoted - technical innovation, greater productivity, alternative energy supplies -are effectively calls for introducing disequilibria into the economic system on the assumption that the new stable state will be better than the present one.

In this context the instabilities are at least as important as the stabilities, and perhaps moreso at the present. Most of the workshop participants agreed that conventional equilibrium methods alone are unsuitable for examining the systems of interest to us. Thus the research directions in the analytical understanding of nonequilibrium systems already being pursued were reaffirmed, and some new one suggested.

The work thus far has brought to light a fundamental knowledge of the process of self-structuring in societal systems, and how this takes place as a consequence of non-linear, dynamic interactions. It is also clear how the process results in low - or single - order hierarchical structures of a generally non-optimal nature. The structuring of higher-order hierachies and the interactions among hierarchies of various levels is not yet clear.

Both catastrophe theory and bifurcation theory are being examined as a way of understanding changes in state and the critical factors at bifurcation points. It is apparent that we are still in the process of placing these mathematical theories in perspective with the larger body of work. Gratifying progress is being made, and this line of inquiry should also continue.

Elements of the theory of chaotic behavior of complex systems have been introduced for exploring macro-economic systems and also for examining urban population and employment dynamics. While some of the ideas presented at the Workshop were embryonic, they appear to have the power to explain analytically some of the otherwise mysterious behavior that has been observed in societal systems.

3. Hierarchical structures

The insights gained from the work on self organizing systems, plus those from hierarchy theory are leading to conceptualizations of a society as a set of dynamic, interlocking hierarchies from order one through at least five, of which government is a part. Further, it appears that higher order hierarchies can interact to form lower order structure (e.g., corporations in a market). Higher order structure can emerge from lower order structure, although this is not inevitable. Higher order structures that are ineffective can also break up into lower order structures.

Transportation and communication appear to be very strong factors in this dynamic, perhaps dominating all others. If this is true, then it is essential that DOT policy analysts understand their roles, for to a great extent the initiatives of the department can be described as attempts to influence social structures.

Much more needs to be known about these structures, their origins and dynamic interactions. It is clear, however, that the matter of hierarchy must be approached in coordination with the investigations in decision theory and nonequilibrium systems.

4. The work in modeling travel behavior under the constraints of time and money budgets has progressed nicely. However, it must be expanded to include a variable urban representation. This requires an exploration of other elements of the household budget. The dynamics of the process must also be added, and it must be more closely related to the work in decision processes and in non-equilibrium systems.

5. A cultural framework.

A framework to relate the physical, organizational and value aspects of a society appears more than ever to be a requisite to understanding the impacts of government actions. DOT, certainly, operates in all three areas, although not always with a clear distinction. The anthropological community is divided on the issue of a proper representation of the components of a society, and subject of dynamics has just barely been touched. However, the field is progressing rapidly and it appears that a resolution of these difficulties will occur before very long. The incorporation of these advances into societal systems and transportation analysis should therefore continue so that all the topics discussed above can eventually be related under a general cultural framework.

6. Empirical research.

This subject received rather little overt attention at the Workshop, yet it is important that we not lose sight of its significance in the rush of theoretical extensions and model development. It would seem advisable to address this topic specifically at the next workshop so as to insure that our observations of the real world keep pace with and complement the advances in theory. There may be nothing more practical than a good theory - but if we can't test it we'll never know.

INTRODUCTION

In modelling the highly complex urban-regional system, it is necessary to choose those aspects of the total system which may be modelled and separated out, which problems of the system we most want to understand and which conceptualizations of the svstem capture the most important system processes.

The papers in these Proceedings treat a number of different problems of the urban-regional system according to the authors' conceptualization of how the system is best understood and modelled. The problems treated and the conceptualizations used are summarized in this Introduction. The papers have been grouped, as much as possible, by the paradigm or conceptualization used by the authors.

The first set of papers all pretty much espouse a self-organizing urban-regional system that is often enough in disequilibrium that its evolution is profoundly affected by these non-equilibrium states. It is conceptualized as a system in which highly non-linear interactions take place and one whose evolution depends upon the system's history and the fluctuations it experiences.

A recurring theme in the papers by P. Allen and D. Kahn is that fluctuations are always occuring which test and probe the system. If the system were in equilibrium, then the fluctuations would have no lasting effect. If the system, however, is far from equilibrium then the fluctuations may take hold and become amplified.

These fluctuations are a form of insuring diversity in the system. In other words, diversity in a system occurs naturally as fluctuations are always occurring. And if the urban or regional system is far from equilibrium, the system begins to distinguish between small differences because correlations begin to appear where they did not exist before. And thus a small fluctuation at the right place and time may start the system on a new evolutionary path. Put another way, local events can have global repercussions throughout the system.

The particular structure or the particular model of behavior to which the system moves depends upon the nature of the fluctuations and upon the conditions prevailing. The structure adapts to outside conditions as it perceives differences in the outside world (which it never would have if the system were in equilibrium). Thereby, the history of the system is very important to the type of structure formed, because where the system is now depends upon which evolutionary branch it took in the past; and where the system will go in the future, similarly, depends upon where it is now.

Thus, the particular type of fluctuation, the particular innovation, the particular technology, the particular political person are all important elements in influencing the direction in which the system will move. In the words of I. Prigogine, the universal and the deterministic give way to a complex dialetic between chance and necessity; that is to say, the evolutionary path a system will follow depends not only on the micro laws of economics, of social interaction, of physics that exist between bifurcation points, but also on the very existence of bifurcations themselves, which leads to macro structure and the amplification of fluctuations whose occurrences are often unpredictable.

Fluctuations also play an important role in policy: one often finds that several theoretically possible stable stationary states of a system exist, so that either of these could be adopted by the system. Which one of the stable stationary states the system adopts depends upon the magnitude and nature of the fluctuation needed to push the system over into one or the other state. This "fluctuation," of course, could be a policy initiative.

As the Allen and Kahn paper stress fluctuations and the self-organizing, bifurcating aspects of a system, the adaptive economics paper of R. Day stresses similar aspects of the economic decision maker. He is no longer a fully optimizing creature, rather, he is recognized as one who deals with the world in a sub-optimal way, lacking complete information. The economic decision maker is very much a part of an evolving dynamic system in which non-optimal actions are being taken all the time by the actors of the system.

There is, however, room for what Day calls the creative intelligence to intervene when needed, to override the system, so to speak. In other words, the socio-economic system may be running along more or less smoothly with perturbations, probes and tests to the system not having much effect, however, the possibility always exists that the creative intelligence may cause a bifurcation in the system. Now, this has to be understood in terms of the conceptualization of the system as a self-organizing adaptive system. It is missing the point to think of this creative intelligence as something that is outside the self-organizing process; the creative intelligence occurs within the diversity of real systems. That is, it is there and when needed, emerges to affect the system when the system is most sensitive to that input. And that occurs when the system is near one of its bifurcation points. The closer to a bifurcation point, the more it disregards the universal and is sensitive to the particular, to the creative intelligence.

As a one sentence summary, we may say that Day's paper shows how adaptive economics and its recursive programming methodology may be used to study the dynamics of urban change employing economic concepts of optimality but which are always ameliorated by the sub-optimal behavior of the decision makers in the economic system.

D. Dendrinos and J. Beaumont, et al., in their papers, also conceptualize the urban and regional system as a dynamic non-equilibrium system. Dendrinos analyzes population data of U.S. Standard Metropolitan Statistical Areas (SMSAs), using bifurcation theory to help uncover the "inner mechanisms of urban dynamics." They find some rather interesting population behaviors and develop a model which captures some of these observations. They recognize the importance of fluctuations and external events affecting the dynamic evolution of the SMSAs, including government actions and technical innovations. They, thereby, conceptualize system evolution as an interplay between more or less deterministic paths of growth and the influence of perturbations and fluctuations on this evolutionary path.

Beaumont, et al., in their paper, further emphasizes this conceptualization of the urban-regional system as a non-equilibrium, non-linear system. They show how the present state of the system, or the state of the system at any future time, depends on the initial conditions of the system and its environment, that is, on its history. Furthermore, they stress the non-linear interaction between the variables of the system including the demographics and socio economics prevailing and show how these interactions lead to an evolving complexity, particularly as thresholds for stability are exceeded, allowing new modes of system behavior to emerge. The idea of thresholds for stability being exceeded was not mentioned previously but this is an important aspect of system evolution. Bifurcation in a system occurs when thresholds for stability are exceeded, that is when outside influence or internal fluctuations cannot be absorbed by the system; the system is said to be unstable to those outside influences or internal perturbations. When this occurs, a new state of the system will emerge which is stable to the internal fluctuations or outside influences. The paper properly emphasizes the importance of stability considerations in the evolution of a system.

For the final paper in this section we chose Richmond's paper, which though not strictly falling into the same conceptualization, nevertheless has one very important view in common with it. And that is the concept that man is not simply a recorder of events but is a partner in the evolution of the urban system.

Richmond explores the importance and relationship between people's self-concept and the operation of the system: in Richmond's terminology, the relationship between the metaphysical and the physical.

In particular, Richmond explores the relationship between the physical plant, a housing project, and the self concept of its inhabitants. In general, man no longer is an outsider, waiting in the wings for the world to become; instead he has an important say in the becoming of that world. The housing project created ostensibly for his comfort may easily be "uncreated" by him. If there is a dissonance between self-image and the image of the housing project, then one or the other will change. From another perspective, here is a system which is far from equilibrium whenever the physical plant and the inhabitant's self-perception differ greatly. This is when change is likely to occur according to disequilibrium theory. This is when the system is most sensitive to change: one possibility, of course, is the destruction of the physical plant, another possibility, obviously much more preferable, is to bring the self-perception of the inhabitants more in congruence with that of the housing stock. Richmond offers a suggestion for accomplishing that.

The next section offers a physical science conceptualization of urban and regional systems. The paper by A. Iberall in this section argues that modern physics is quite capable of dealing with complex systems and that the principles of physical science can and should form the basis for a theory of complex systems. Iberall then develops a parsimonious set of basic physical principles or conservations which, along with a given set of potentials, form the basis of a physical science of social systems. While he recognizes the role of fluctuations and disequilibrium phenomena in nature, his construct is predominately one of a system which is locally near equilibrium.

In the next section, Ragade espouses a living systems conceptualization, calling for identification of the "critical processes" and their dynamic interaction in the urban-regional living system. This conceptualization does not rule out disequilibrium phenomena, but it does emphatically stress the methodology and paradigm of living systems theory for understanding urban and regional systems.

The paradigm espoused by M. Mesarovic in the next section is a conceptualization of a multi-level city structure that recognizes the important role of hierarchies in the complex urbanization process and whose behaviors are goal seeking and decision oriented.

Pluralistic decision making is emphasized in the Cruz paper, suggesting that the decision making in the system can be separated from the "natural dynamics" of the system. Bifurcation phenomena and non-linear system behavior are recognized as important natural phenomena of system behavior by Cruz but stresses that a realistic understanding of the causes of these phenomena of urban systems requires explicit consideration of pluralistic decision making.

Choukroun and Harris present a review of urban-regional models, total and subsystem modeling, multi-activity modeling; discuss philosophies of the models and address the important issue of equilibrium/disequilibrium models. They point out that equilibrium models of non-equilibrium structures can still give important information on urban processes that may be in an equilibrating condition. The paper then describes their own ongoing work in locational modeling, stressing the mutual interdependence and relationships between interacting urban activities.

The paper by Golob and abstract by Beckmann address continuous modeling approaches (as opposed to discrete modeling). Golob presents research on the concept of travel probability fields and Beckmann suggests a continuous flow representation to represent urban interactions. More generally, Golob's paper and that of Zahavi which follows, are concerned with how to model a system with the least biases and the smallest number of factors that depend upon the particularities of place and time of the modeling. They look for certain basic behavioral characteristics or preferences. If these can be found and used as constraints in the modeling process, then the models should be valid not only for the particular place being modeled and for the particular time for which the data was recorded, but for all times and all places for which those basic human characteristics and behaviors are valid. Finally, the paper by N. Oppenheim presents an application of the UMOT model, developed using these concepts, which addresses some typical urban transportation policy questions.

The next section contains a paper by A. Keaton in which the use of ecological type models in sociology are discussed and assessed; and a paper by B. Seagraves-Whallon in which an attempt is made to place the urban-regional system within a general socio-cultural context, and to understand its organization, operation and dynamics.

The final paper by D. Ramsett and P. Smith provides a discussion of equilibrium and disequilibrium modeling for urban and regional systems and attempts to rationalize the disparate views of economists and physicists on this subject.

A. SELF-ORGANIZING, BIFURCATING SYSTEM CONCEPTS AND ADAPTIVE ECONOMIC APPROACHES IN URBAN AND REGIONAL MODELING

SELF-ORGANIZATION IN HUMAN SYSTEMS

by
P.M. Allen

ABSTRACT

In recent years new concepts have emerged for the natural sciences related to the self-organization or structural evolution of complex systems. This new paradigm is discussed, and several applications in the field of economics, and urban systems are described.

INTRODUCTION

In our attempts to understand and 'deal with' the complexities of the world around us we commonly construct 'models' either intuitively in our heads, or explicitly by setting them down on paper. The essence of modelling is that it be a 'reduced description' where 'superfluous' detail and particularity are passed over, and only the essential remains. Briefly then we search for something which is easy enough to work with, but which nevertheless captures and governs what we consider to be the important features.

Yet we often have cause to ask : what level of description is really required to describe the evolution of a particular system ? Often a 'system' analysis or a 'model' of a system is written as a set of interacting differential equations describing the time rate of change of certain 'variables'. These latter are usually aggregate or average 'variables' over the system or some region of it, and their change in time is supposed due to the occurrence of 'typical' processes expressing average behaviour.

The first fundamental point of divergence of common sense with many 'models' is their 'determinism'. The question we must ask is : when is the passage from a complex, complete real system to a reduced, deterministic description adequate ? The answer has recently become clear as a result of progress made in the natural sciences concerning the origin of structure and organization in the universe (Glansdorff and Prigogine, 1971). In systems at or very near to thermodynamic equilibrium the macroscopic, reduced description is valid. However, for systems which are far from equilibrium, open to flows of energy and matter then non-linear interactions can lead to a breakdown of the macroscopic description because of the possibility of bifurcation and of the multiplicity of solutions. Where bifurcation occurs the reduced description is inadequate.

Consider the modelling of the growth of a population X inhabiting a region with limited resources. The basic description is simply to suppose probabilities of birth and death due to the different processes going on in the system, and to construct the so-called 'Master equation' which governs its evolution. This essentially considers the net in or out movement per unit time for each 'slice' of probability P(X,t) and in this way generates both the movement and change in shape of the probability distribution in time.

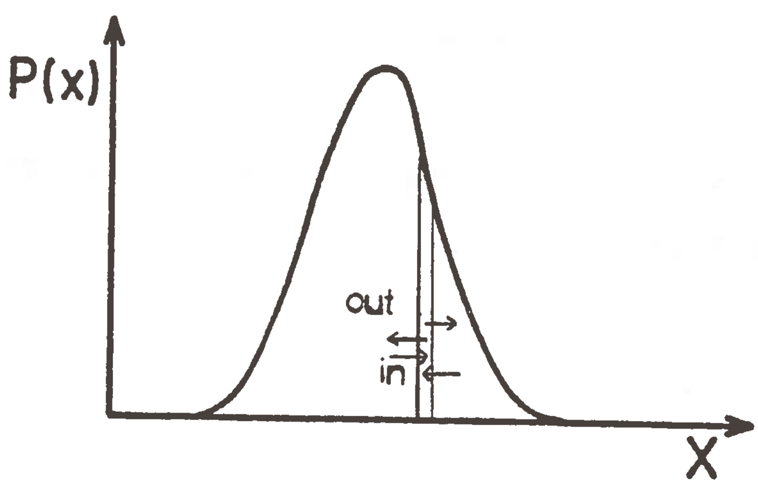


Fig.(1). Probability distribution of X.

Now if we study the change of the average value of X, we must simply multiply the master equation (1) by X and integrate over all X. The 'first moment' approximation as this is known then tells us how the average values of X changes as a result of the various processes which cause the increase or decrease of X. If, for example, we consider a probability of birth per individual per unit time which depends on the quantity of resources left in the system :B(1 + X/N), and the simple probability of death per individual per unit time, M then, we have for the Master equation :

$$\frac{dP(X,t)}{} = B[(X-1)(1+X/N)P(X-1)$$

$$- X\left(1-\frac{X+1}{N}\right)P(X)]$$

$$+ M[(X+1)P(X+1) - XP(X)] \qquad (1)$$

and multiplying by X, integrating and considering unit area of the system we find :

$$\frac{dx}{dt} = bx\left(1-\frac{x}{N}\right) - mx \qquad (2)$$

the logistic equation, where x is the density of individual, and b and m have dimensions of inverse time, N is the density of resources in absence of x.

Typically, we have a dynamics of the type shown in fig. (2).

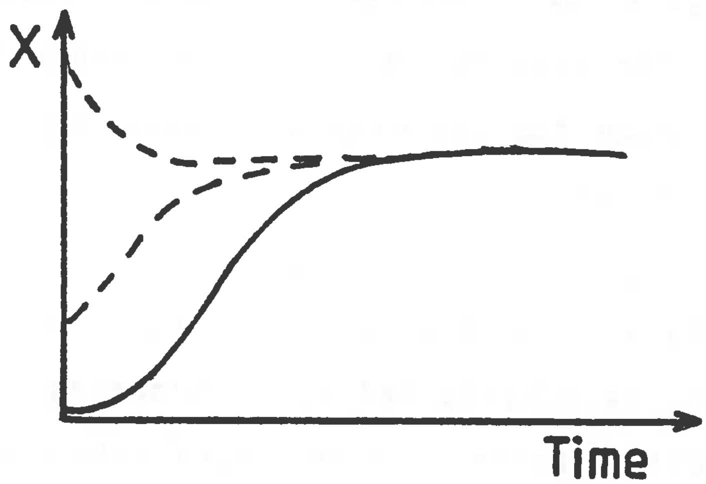


Fig.(2).Dynamic growth or decline according to equation (2).

However, if we examine more carefully this equation, then we find that it affords a very simple example of bifurcation. We note that for example, $x = 0$ is always a solution. That is $\frac{dx}{dt} = 0$ when $x = 0$. However, there may exist a second solution, $x=N(1-m/b)$ corresponding to a real positive solution provided that $b > m$. Thus we may say, that a study of the stationary states of the kinetic equation does not permit to us to say unambiguously what the population of the system is for $b>m$. It could be $N(1-m/b)$ or 0, and at present we have no information which.

However, extra information can be obtained by studying the kinetic equation and thinking about the 'stability' of these two solutions. Since in the real world we know that the actual density of the population x will fluctuate around the average values predicted by the mathematical model (2), then in the real world for a stationary state to persist, it must have the property of 'resisting' or 'damping' such fluctuations.

The stability of the two possible states $x_1 = 0$ and $x_2 = N(1-m/b)$ can be ascertained by considering the behaviour of the kinetic equation for arbitrary values of x. In this way, we have marked on a diagram the direction of motion of x (either increasing, or decreasing) that the kinetic equation obliges for any particular value of x fixed N and m, where $N > 0$ and $m > 0$ and for different values of $b > 0$.

This allows us to draw the diagram (3) showing the global stability properties of the system.

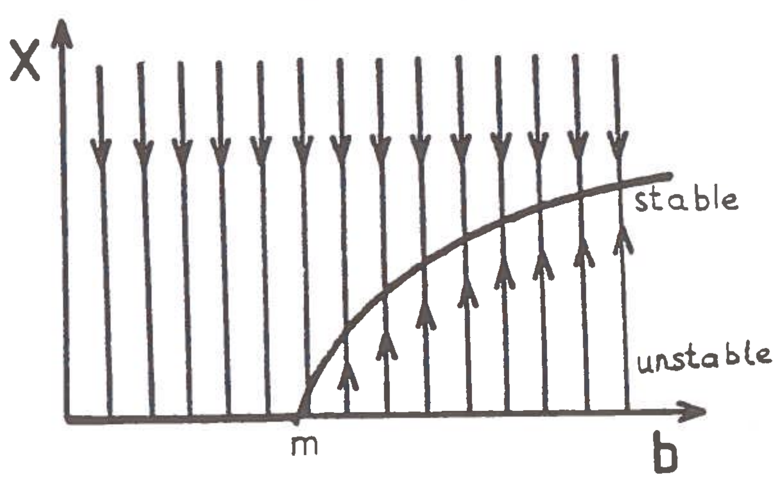


Fig.(3) A diagram showing the behaviour of the system and its global stability properties.

Thus, when $b < m$, there is only one solution, $x_1 = 0$, and this solution is globally stable, attracting all initial values of x. When $b > m$ however, there are two solutions, but $x = 0$ is unstable.The solution $x = N(1-m/b)$ is stable and attracts all initial values of x as shown in fig.(3).

This rather trivial result, can be made considerably more interesting if we write the 'mortality' term m, in terms of the disappearance of x because of a predator, whose density we shall suppose fixed, and which 'grazes' on the prey x when it encounters it. However, when prey is abundant, we will suppose that each predator can only eat his 'fill', and therefore total consumption of x cannot exceed some maximum value per predator. The simplest term which represents such a situation is the following :

$$mx = \frac{Syx}{1+x} \qquad (3)$$

where, when x is small ($x \ll 1$) then the rate of decrease of x is proportional to the rate of encounters between predator and prey (Syx) while if x is large, the rate of consumption of x is simply proportional to the density of predators (Sy).

Our modified equation reads :

$$\frac{dx}{dt} = bx\left(1-\frac{x}{N}\right) - \frac{sxy}{1+x} \qquad (4)$$

Again, x = 0 is always a solution, but there are possibly two other solutions given by the quadratic equation :

$$x^2 - (N-1)x - N(1-sy/b) = 0 \qquad (5)$$

which leads to

$$x^- = \frac{N-1}{2} - \frac{1}{2}\sqrt{(N-1)^2 + 4N(1-sy/b)}$$

$$x^+ = \frac{N-1}{2} + \frac{1}{2}\sqrt{(N-1)^2 + 4N(1-sy/b)} \qquad (6)$$

The behavior of the system as a function of b is shown below :

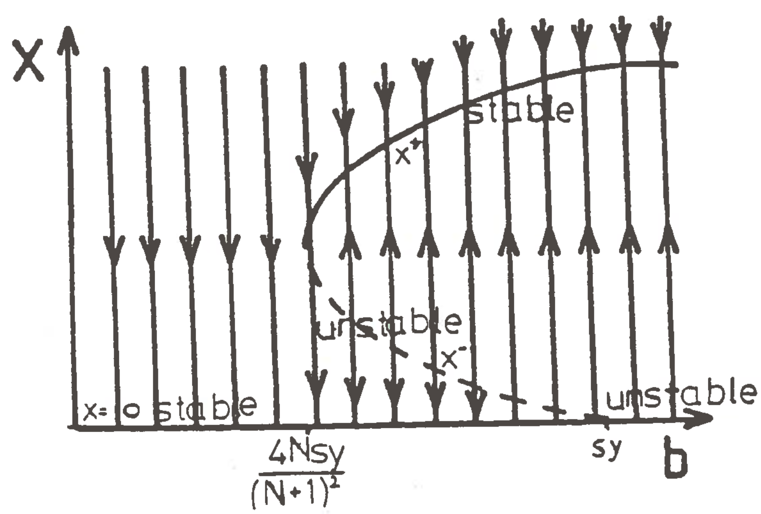


Fig.(4). Solutions x as a function b.

Thus, for $b < \frac{4Nsy}{(N+1)^2}$ we have one stable root $x = 0$.

for $\frac{4Nsy}{(N+1)^2} < b < sy$ then <u>both</u> $x = 0$ and x^+ are stable, th ough x^- is unstable.

for $b > sy$, we have only a single stable root, x^+.

Here we see that for a certain range of parameter values, we have three simultaneously possible solutions for the deterministic, average equations, and now even stability analysis does not suffice to confine the system to a unique state, since two of there solutions are stable. Thus, in reality, the state which we shall observe for a particular case will depend on its history. This is a first very simple example of how the concepts of 'memory' and of 'choice' enter into a problem described by a set of macroscopic equations.

The importance of this particular model for agriculture, fisheries and any exploitation of a naturally reproducing species can be seen by considering the 'bifurcation' diagram drawn for a fixed b and N, but for increasing numbers of 'grazing' species y.

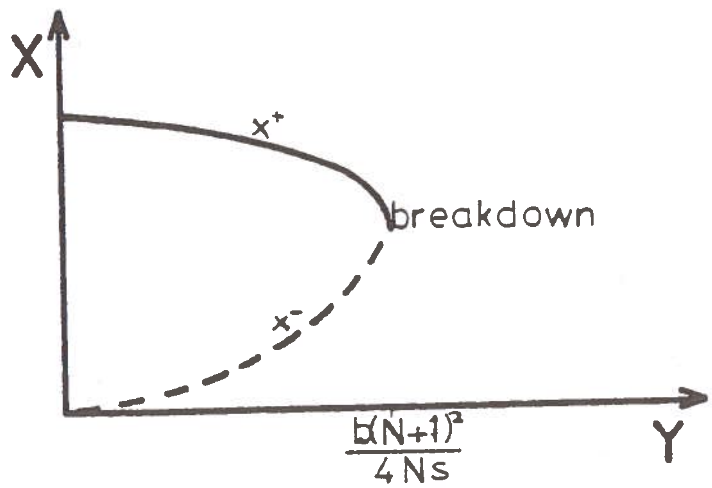


Fig.(5). Possible solutions of x as a function of increasing grazing y.

Thus, increasing the grazing herd steadily,at first leads only to gradual decrease in the density of the prey. However, at a certain point, only a small increase in y, produces a sudden collapse of prey numbers, that will entrain the subsequent dissapearance of the grazing herd and a breakdown in the system.

In reality, the calculation of this critical point must take into account the precise nature of the fluctuations of population, of b of N and of S, for on these will depend the level of grazing which can be maintained without risk. Failure to do this has led to ecological and economic disasters in the past !

In chemistry some very much more complex bifurcations have been studied, giving rise to many different possible solutions of the chemical kinetics, solutions which differ qualitatively. For example, the reaction scheme,

$$A \longrightarrow X$$

$$B + X \longrightarrow Y + D$$

$$2X + Y \longrightarrow 3X$$

$$X \longrightarrow E$$

where X produces Y, which in turn produces X has been intensively studied by the Brussel's school (it is even known as the Brusselator) and various different types of self-organization have been found. By regulating the flows of the initial and final products, A, B, D and E, one can move away from equilibrium and, at a certain critical distance an instability occurs. This threshold marks the point at which the least fluctuation can cause the system to leave its uniform stationary state.

When this occurs a fluctuation is amplified and drives the system to some state characterized by the coherent behaviour of an incredible number of molecules, forming perhaps a moving zone of high concentration of component - a chemical wave - wherein the chemical reactions maintain the spatial organization.

These are 'dissipative structures' new, organized states of matter some examples of which are shown in the figures (6) and (7). They correspond to organizations of the system which exceed by many magnitudes the scale of the interactions between the individual elements, in this case molecular forces, in fact over lengths related to the non-linearities and the diffusive forces in the system. All that is required by a structure to 'explain' its persistence once it has arisen stochastically from an instability, is that it be stable.

This description contains both deterministic mechanisms (the chemical equations) and stochastic, random effects (the fluctuations) and it is these latter that are of particular importance when the system is near to points at which a new organization may change. These points are called bifurcation points.

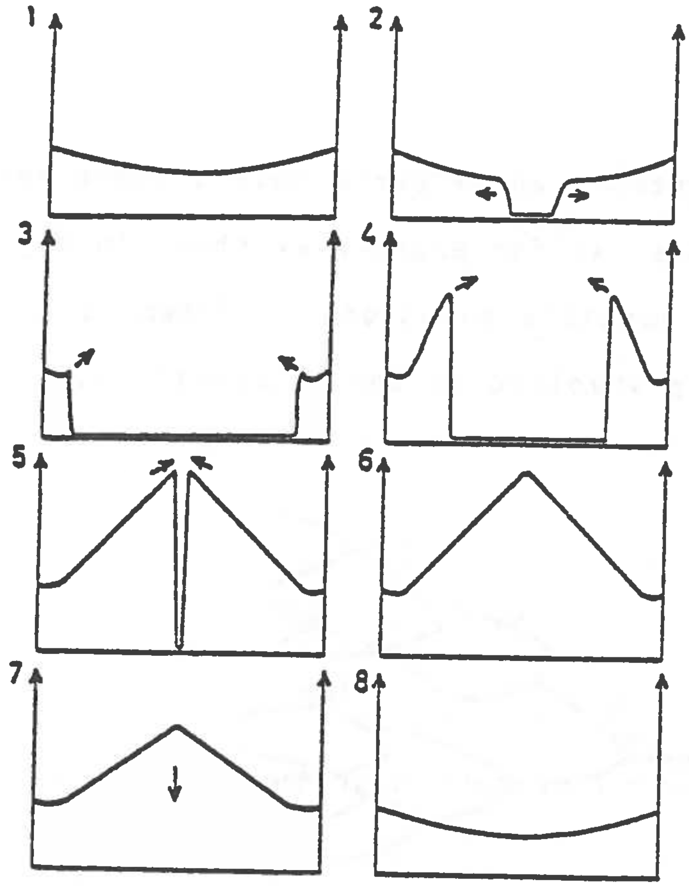


Fig.(6). A cyclic spatio-temporal stucture of propagation : chemical 'waves', as the concentration of intermediate X follows the sequence indicated in 1⟶8.

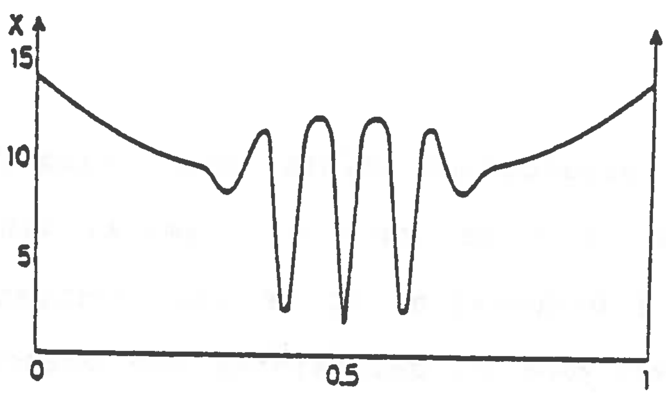


Fig.(7). If we allow for the diffusion of A into the system from the walls, then we can have the formation of a dissipative structure having its own length scale.

Complex systems can ofcourse have a whole series of bifurcations points, as for example we show in fig.(8), where the diagram of possible solutions is drawn as a function of some parameter p involved in the interactions.

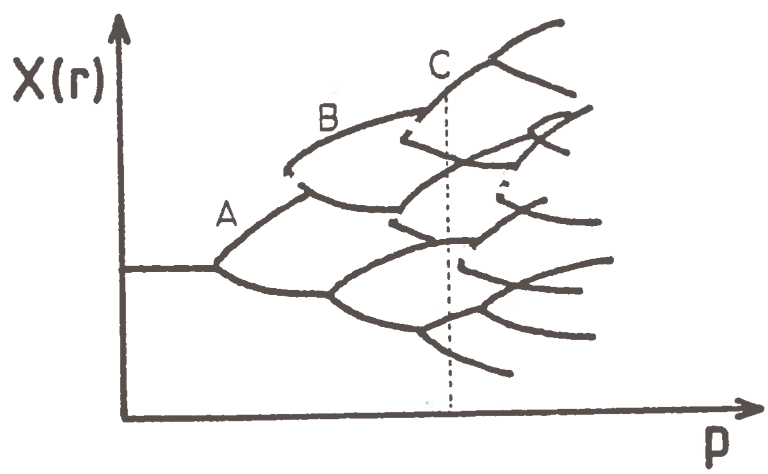


Fig.(8). A bifurcation diagram showing the possible solutions as a function of parameter p involved in the interaction.

Between two bifurcation points, the system follows deterministic laws (such as those of chemical kinetics) but near the point of bifurcation it is the fluctuations which play an essential role in determining the branch that the system chooses. Such a point of view introduces the concept of 'history' into the explanation of the state of the systems. For example, in fig.(8), the 'explanation' of the fact that the system is organized according to the solution

C, necessarily refers to the passage through the structures B and A. No 'explanation' can ever deduce the unique necessity of finding the system in state C for the particular value of the parameter P.

A vital point that must be understood is that these two different aspects of evolution correspond to situations 'far from', or 'near to' a bifurcation point. In reality, what we have is that far from a bifurcation point, the probability distribution is sharp and singly humped. Thus the 'average' or macroscopic equations of our model (the first moment approximation) effectively govern and determine the state of the system. However, near a bifurcation point, the non-linearities on the interactions cause the probability distribution of the underlying stochastic process to kink, and lead to a double humped distribution.

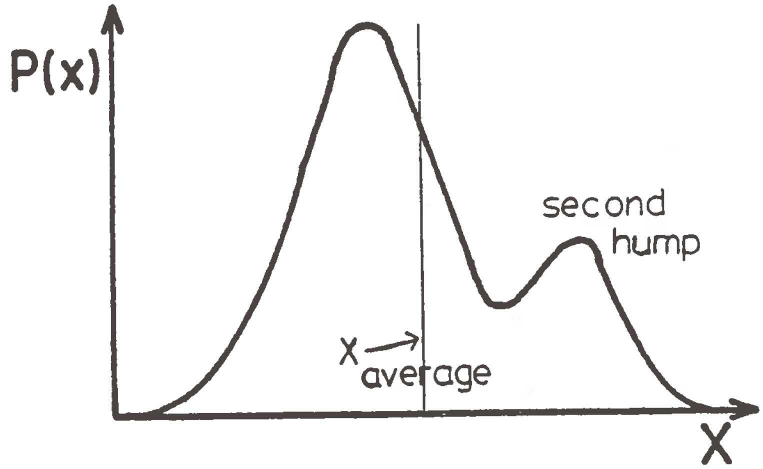


Fig.(9). Appearance of a second hump due to non-linear interactions.

Thus, the first moment or average description is now hopelessly inadequate to describe what the system will now do, and in fact what occurs is that the system may jump to one or other of the humps. An important remark concerns the 'danger' of interpreting the behaviour of a system as being governed by a potential function. For example, one could, retrospectively construct a 'potential' which behaved as some inverse probability func tion,

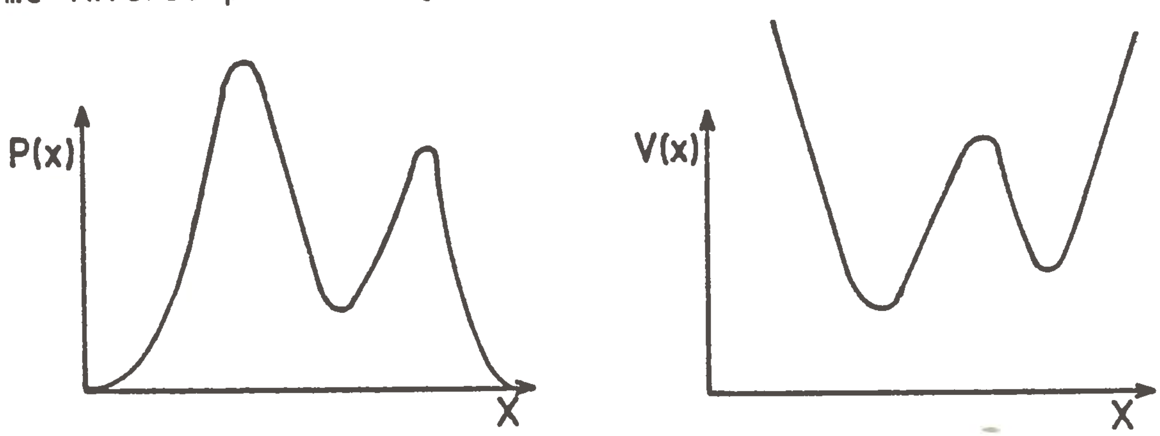


Fig.(10).

a) Double humped probability distribution

b) Potential well designed to 'mimic' (a).

but in general such a construction serves no purpose. Firstly, for more than one variable it is in general impossible to construct such a function, meaning that the class of non-linear dynamical systems contains as a small subset thos derived from a potential function. Secondly, we must recall that the differential equations of our 'model' are in fact only the first moment approximations to the master equation and that it is this latter equation that really governs the system. Thus, even for a one variable problem where it is possible to intergrate the right-hand side of the differential equation in order to obtain a potential function, there is no guarantee that this will <u>in fact</u> imitate correctly the true shape of the probability distribution. For example, it is true that we can integrate, the logistic equation $\frac{dx}{dt} = ax - bx^2$ to give a 'potential', ($V(x) = a\frac{x^2}{2} - b\frac{x^3}{3}$), but in reality, we could have different stochastic dynamics underlying the first moment approximation. For example, the presence of term :

$X \longrightarrow X + 1$ with probability $\frac{AX^2}{2}$

and

$X \longrightarrow X - 1$ with probability $\frac{AX^2}{2}$

does not change the 'average' equation, but does change the 'shape' of the probability distribution P(X,t), and hence the 'potentials' obtained by integrating the first moment equation would mimic incorrectly the behaviour of the system when perturbed from its stationary state. In a word then, the clean, closed, geometrical world of potentials and catastrophe theory is in general not relevent to the real, somewhat messy but much more interesting, world of complex systems evolving through successive structural instabilities.

This type of evolution, involving both determinism and chance, has been called 'order by fluctuation', (Nicolis and Prigogine, 1977) and we see that this extension of the physical sciences offers us a paradigm which is potentially of great importance for the biological and social sciences (Prigogine, Allen and Herman, 1977). There is already an extensive literature concerning different applications of these new ideas in various domains. In the study of oscillatory biological phenomena (Goldbeter and Caplan, 1976), (Goldbeter and Nicolis, 1976), for example, and in the problem of 'morphogenesis' (Erneux and Hiernaux, 1979) in the early states of embryo development. Also, the development of models treating the problem of cancerous growth, as resulting from an instability of the immune system, have been made and explored in both steady and 'noisy' environments (Lefever and Horsthemke, 1979). Other studies have been undertaken which explore the role of these new ideas in our understanding of the 'order' that reigns within animal population, and in particular, in colonies of social insects. (Deneubourg and Allen, 1976), (Deneubourg, 1976). We shall not go further into such questions here, but move on to discuss the impact of these new ideas on our understanding of human systems.

2. SELF-ORGANIZATION IN A 'SIMPLE MARKET SYSTEM.

Having mentioned the evolutionary paradigm offered by 'dissipative structures' in the realms of chemistry, biology and ecology we now turn to a brief description of some recent applications to human systems. The characteristic of such systems is that they are made up of a multitude of 'actors' of different types, each having its own particular criteria and values, as well as different opportunities and power in the systems.

The economic and social sciences have developed in an attempt to understand and clarify the workings of society, and where mathematical modelling has been used, it has been largely based on the analogy between equilibrium physics (for example, an equation of state P = RT/V). Thus a 'global utility' for social or economic system is often used to 'explain' its evolution, in a manner akin to the 'increase' of entropy characteristic of an isolated physical system. Similarly, some polynomial form is often supposed to express this 'global utility' or potential and since this can lead to multiple solutions,to folds and cusps, the evolution of the system as a whole is 'pictured' as being one of movement along this surface, and of 'catastrophic' jumps between them. It is our contention that for most complex systems, particularly humain containing ones, this analogy is in general false, and that the 'construction' of such a potential can only be performed 'after the event' and as we have discussed above only constructed to 'mimic' what has been observed and which in fact results from the complex dynamic interplay of the decisions of different actors.

What we are concerned with throughout this paper, is what Herbert Simon has called the ineradicable scandal of Economic Theory - imperfect competition. In reality this scandal extends over the whole of social science and biology and concerns, the dynamic interaction of what can only loose be called 'supply' and 'demand'. It concerns emergence of structure and organizations in open systems.

In order to proceed further, we must now try to identify the significant actors of the system, whose decisions, and the interplay of these, will result in the particular patterns of consumption observed. These we shall suppose to be consumers of varying wealth and taste, and entrepreneurs investing in the production of particular products, and adopting different possible strategies to secure and make profitable this investment.

The next phase of modelling is to attempt to construct the interaction mechanisms of these actors, which in principle requires a knowledge of their values and preferences, and ofcourse how these values conflict and reinforce each other as the system evolves.

How can several different criteria be 'combined' in order to given a measure of the probability of a particular decision ?(Roubens, 1980) The basic idea accepted by multicriteria analytists is that we may suppose that a given actor is at least conscious of some major criteria, in each of which he can define a direction of preference, and also that in addition, he can assign some measure of their relative importance, even if it is very vague. Clearly, the idea of a 'pay-off' which will occur in the future following an action involves the actors capacity to believe that he can predict the future over such a time. Thus it depends on his confidence in the 'model' he is using. This is yet another aspect of 'learning', which as we shall see permeates the discussion of modelling in human systems.

Another vitally important factor which must be included in any modelling of decisions is the fact that we have in general non-linear responses to given changes in stimuli. In general then the problem of assigning a number to a given value of a criterion such that it measures our 'reaction' and 'sensitivity' to that reading, comes down to some non-linear projection. However, such an approach will also open the door to the consideration of qualitative factors, for in reality there is no difference between the input of a 'quantity' to which we may be unduly sensitive, and a 'quality' which although the input is not strictly a number, nevertheless may have a number assigned to it.

A particularly clear way of visualizing the problem is to suppose that the axes corresponding to each criterion have a common origin, which represents the 'ideal', the most preferable solutions imaginable. For example, we may wish for the biggest, fastest, most comfortable car, butwhich costs zero money ! If this is the origin of our value space, then in fact the choices open to us will be out away from this origin, offering various compromises of size, speed, comfort and price. The question is, how are these different possibilities perceived and weighed by individuals?

Let us suppose that we consider two choices only, and that the axes are viewed as having importance (α_1, α_2, α_3).

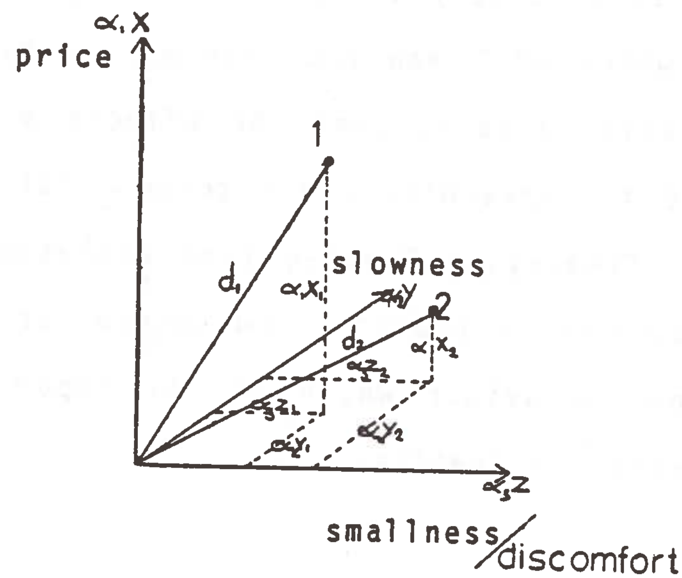


Fig.(11)

The two choices viewed by this individual are now some distance from the origin, and in general we see that these 'distances' should be calculated using the formula,

$$d_1 = \sqrt{(\alpha_1 x_1)^2 + (\alpha_2 y_1)^2 + (\alpha_3 z_1)^2}$$

$$d_2 = \sqrt{(\alpha_1 x_2)^2 + (\alpha_2 y_2)^2 + (\alpha_3 z_2)^2}$$

Thus if α_1, is increased the probability of choosing the cheaper car is increased.In this simple example then, we have supposed a linear sensitivity to each 'pay-off' value, given by the weights as well as complete certainty as to the values of the pay-offs. In reality, we must admit the possibility that instead of simply using a weighting we should use a 'projector' which will map the 'pay-off' onto each axis or criterion, taking into account the effects of constraints which may lead to thresholds and extreme sensitivity in certain ranges. Clearly, a Boolean type analysis is an extreme example of such non-linearity, and indeed corresponds to a 'satisficing' behaviour which may be important, particularly in uncertain situations.

Another point which should be emphasized is that when ever we examine a decisional problem involving a given set of choices, say which car should we buy for example, it is important to remember that in addition to the given choices of different makes of car, there are the 'other' choices lying outside the 'automobile market'. Thus, in the example, we have considered above, we must add to the two choices we have shown, by considering the 'pay-off' associated with not buying a car. It costs less, probably, but is slower and less comfortable. Thus our diagram should be amended to look as below.

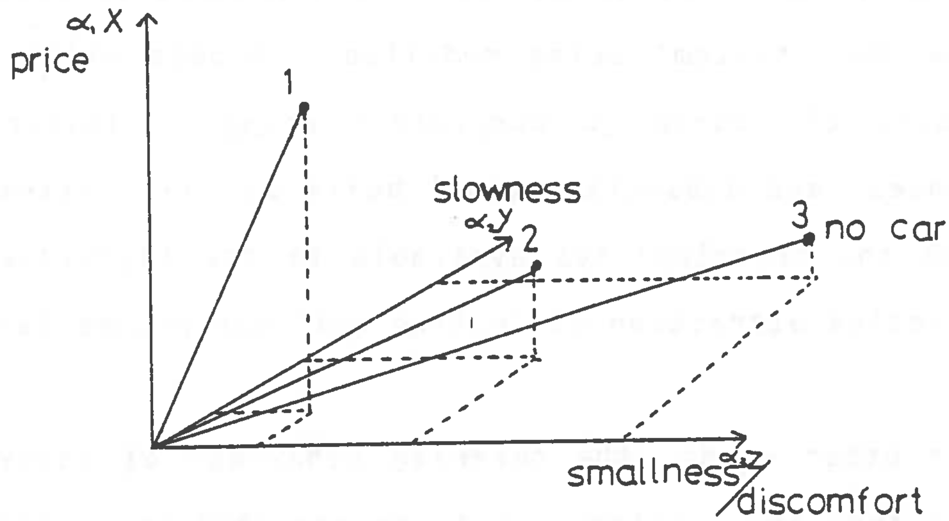


Fig.(12)

The presence of this third choice means that clearly there is some probability that is will be chosen, and what we may note is that as the 'distances' d_1 and d_2 both increases for the 'poor' individual, so the probability of making the third choice increase. This effect will be all the more strong if for example the individual making the decision lives in a locality which is well served by public transport, or where goods and services can be obtained locally, on foot. The presence of this 'external' choice is important in understanding the size of a given market, which will change as the relative 'distances' of the average choice within the system and that of the choices outside change. This sort of effect may be of great importance, for example, in the residential location decisions of an urban population, who may as prices, density and pollution increase within the urban area, switch their preferences to localities outside the 'system' being modelled. Models which ignore this will of course go completely wrong. Similarly, as 'distances' and dissatisfaction' build up in a system, that is with the opportunities available to the individuals, so the relative attraction of 'opting out' may become large.

In other words, the observed behaviour of individuals results from the 'dialogue' between the choices available to them, and their needs and constraints.Adversity can be either a spur to the search for new solution which may lead to an 'instability' and be adopted in the system, or it may lead to a rejection of the system, and to attempts to replace it.

Having digressed somewhat the wider issues underlying observed behaviour and choices, let us now return to the more mundane problems of model building. How can we insert the uncertainty and lack of information which may characterize the pay-offs ? This can be handled quite simply, in the following way. As we have mentioned above it is reasonable to suppose that the probability of making a particular choice is inversely proportional to its 'distance', in the value space of the decider, from the origin. Suppose now however, we wish to consider a situation in which there was no information concerning these distances. If this were so, then clearly, if there are two choices then they have an even change of being selected. On the other hand, if there is absolute certain knowledge that one of the choices is better than the other, then we may suppose that there is a probability of one that it will be adopted. An expression which fulfills these requirements is the following one.

Probability of choice i among all those possible j.

$$P(i) = \frac{A_i}{\sum_j A_j} = \frac{\left(\frac{1}{d_i}\right)^I}{\sum_j \left(\frac{1}{d_j}\right)^I}$$

where I is a measure of the amount of information the individual has to make his decision, A_i is the perceived 'attractivity'.

When $I \longrightarrow 0$ we have equiprobability for all the choices possible, but when $I \longrightarrow \infty$ then we have probability 1 for the choice corresponding to the shortest 'distance'. Of-course, we could also take each axis separately and look at the uncertainty in that, since some facts may known precisely, and others extremely vaguely. However, this would make our calculations very much more complicated in the modelling which we shall present here, and so while not ing that that is the correct procedure, we shall not pursue it further.

The main feature of the approach we are attempting to build here, is that for each type of actor, according to his means and his role etc., he will have a different value space. It may be simply a matter of degree, or, it may also be that we have a quite different set of values, probably related to a different 'role' in society.

So far we have been discussing decisional behaviour without taking into account the fact that the system may be evolving.

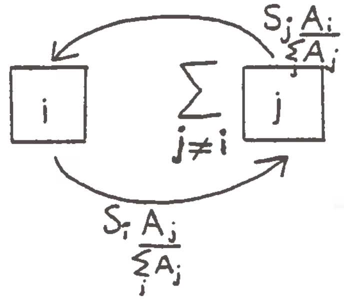
In a dynamic system the 'pay-offs' which characterize each choice will change in time, as will the choices open to individuals, and this evolution will be predicted by the decision maker according to the 'model' he is either implicitly or explicitly using. It is somewhat disquieting to realize that the models we are going to build will contain the behaviour of actors, which will in turn depend on the models available to them. This is an important point because it may influence the confidence which any forecast may be accorded, and in that case the behaviour of actors may be more dominated by 'satisficing' than 'optimising'.We shall return to this point later because it may be of importance in discussing the use to which modelling should be put; that of predicting the future evolution and of making the 'best' decision, or rather of exploring the 'dangers' and 'uncertainties' of the future and attempting to evaluate acceptable and robust decisions.

In an evolving system then, each actor will attempt to estimate the 'pay-offs' associated with a given choice, not only instantaneously, but also over future times, and according to the importance and weighting which he accords to future times, he will decide which choice he prefers.

Let us now suppose that the probability of making a particular decision i, from $\sum_j$ j, per unit time is proportional to the relative attractivity. From this it is now possible to construct kinetic equations governing the evolution of the numbers of individuals adopting each choice.What is of vital importance however, is that as a given option is adopted so the 'pay-off' (costs, prestige, comfort, etc)will change and so the choice pattern of the population will reflect this, as choices get nearer or farther along the different dimensions of various value systems of the actors.

Consider a homogeneous population x faced with several possible choices.

Then, we may write down that for any particular consumption pattern (i.e. number of clients, S_1, S_2,....S_i consumed) then we will have for the ith choice,



Then, if $x = \sum_j S_j$

$$\frac{dS_i}{dt} = a S_i \left(\sum_{j\neq i} S_j \frac{A_i}{\sum_j A_j} - S_i \sum_{j\neq i} \frac{A_j}{\sum_j A_j} \right) \qquad (6)$$

$$\frac{dS_i}{dt} = a S_i \left(x \frac{A_i}{\sum_j A_j} - S_i \right) \qquad (7)$$

and for several populations, x_j each with its own view of the relative attractiveness of the choices, A_{ij}, we have,

$$\frac{dS_i}{dt} = a S_i \left(\sum_j x_j \frac{A_{ij}}{\sum_{i'} A_{i'j}} - S_i \right) \qquad (8)$$

where the attractivity A_{ij} of the i-th choice, viewed by the population type j, is thus some inverse of the 'distance' from the origin of i in the value space of the type j, raised to a power I, as explained above, related to the information available in the system.

In the first example, which we briefly describe here, we have studied the dynamics of a simple market, where products are in competition. We have considered the simplest case, where the 'value' space of the population consists simply of two dimensions : price and quality. The origin of each persons value space is taken to be that his 'ideal' would be the highest quality product imaginable at no cost. In reality, ofcourse, the 'supply' will only offer products where some compromise of price and quality obtains, and customers will be attracted to the various products to different degrees. We have supposed a Gaussian function for the weighting 'accorded' by the different members of the population to the 'price' of a product, which could implicitly or indirectly be related to a Gaussian distribution of income.

Using the equations of type (8) we have studied the dynamic interaction of products, competing for customers, with prices fixed by entrepreneurs by adding a percentage profit to the costs of production, and where we have supposed that these latter increase proportionally with quality.

Now if there were no 'economies of scale', or multiplier effects, no market threshold or psychological effects of fashion, then it is true that an almost infinite number of products could exist each corresponding to the minimum 'distance' d_{ij} in the value space of a particular individual.

However, this is not the case in the real world, where economic and psychological non-linearities abound. Thus, we can show that, depending on the precise sequence of events occuring in the system, that is the moment and size of the launching of each product, as well as the profit margin strategy of each firm, many different stable 'market equilibria' can be attained. For example, the sequence of events may lead, for the same equations of interaction, to either a monopoly, a duopoly or an oligopoly (and in fact many realizations of each), and each of these equilibria is characterized by both qualitatively and quantitatively different flows of goods. In fig.(13) we see the state attained for a particular set of parameter values in equation (13), when all three products start at the same moment with 10 units of production.

Quality 1 = ·3
Quality 2 = ·5
Quality 3 = ·6

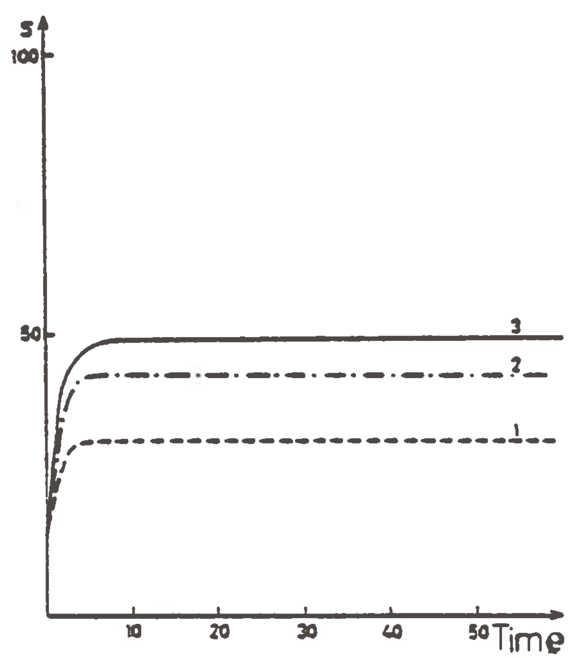


Fig.13.

In fig.(14) however, we see that for the same system there are different possible outcomes which depend simply on the timing of events. For example, if product 1 is launched first then its sales volume moves to the stationary state indicated, assuming that its profit margin remains at 20%. Ofcourse, in the event of monopoly, the firm may modify this profit margin, and this possibility could ofcourse be studied by our model but we shall not concern ourselves with this point here. If product 3 is introduced 10 units of time later, we move towards the duopoly indicated by the levels 1 and 3. If at time t = 20, we attempt to launch the product 2 in the market, we find that an initial size of ten units of production is no longer sufficient to allow its implantation. In fact, it can only establish itself in the market at this moment providing it has an initial production scale of at least 19.5 units. If this is the case then the system evolves towards the stationary state indicated by the levels [1], [2] and [3].

Already, our simple study reveals that the later a firm arrives in a mar ket, the greater the initial investment that is required for it to establish itself. Therefore, whatever 'market equilibrium' we observe for a particular system will depend not only on its precise history, but even on the 'size' of investors that have as yet remained outside this market !

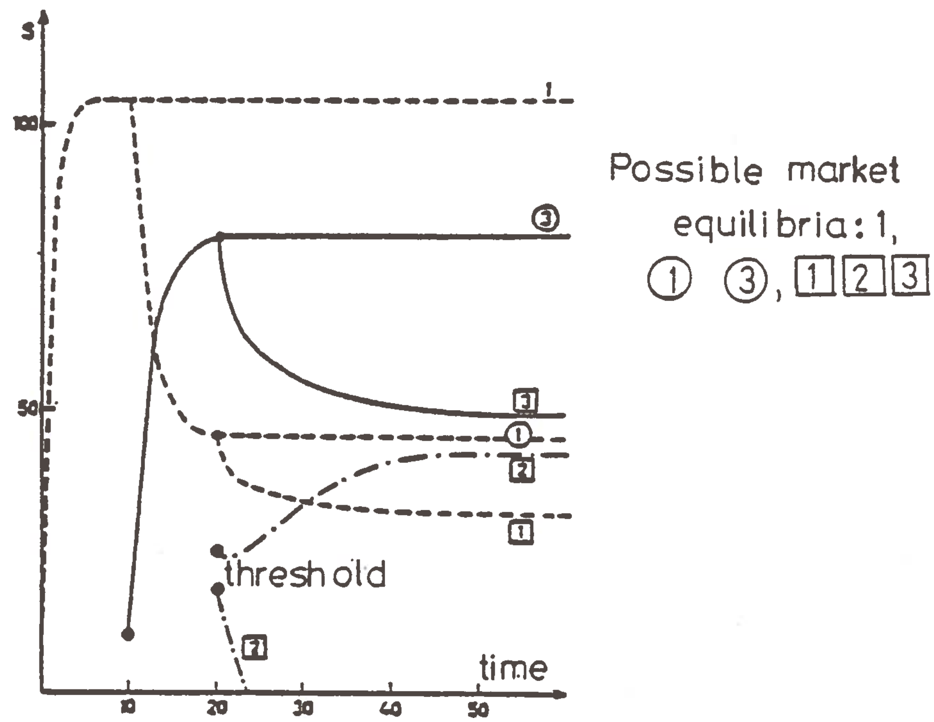


Fig.14.

Similarly, the particular strategies of different entrepreneurs also determines which stationary state is attained by the system, as is shown in figure (20) where we show the possible effects on the market of the decision of a firm to reduce its profit margin. The long term result depends on the type of retaliatory measures adopted by its competitors, and in particular depends on their 'reaction times', for if these are too long then they may fall below the survival threshold.

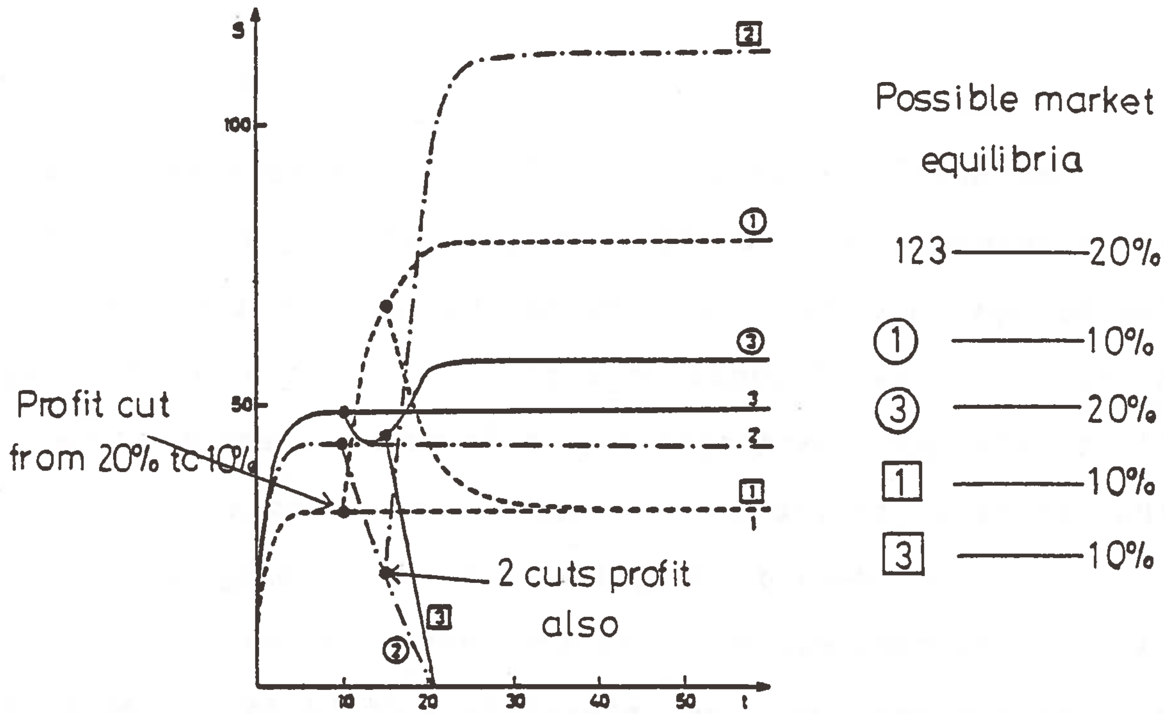


Fig.(15)

We see the irrepressible tendency of an 'unstructed system' of initially equal sized firms to 'structure' or organise itself into a hierarchy of firms, each with different power, to act on the future evolution and the tendency for this structuration to lead to collusion, cooperation and in general an escalation of the 'scale' of coordination involved in the competition. Such a model offers us the basis for an understanding of the origin and evolution of organisational hierarchy in an initially unorganised situation. Ofcourse many other studies have been made using these simple equations, exploring the effects of different market strategies, of cartels, of product specialization etc. but we shall not discuss these further here. (Allen, Frere and Sanglier, 1980).

The most important point of principle is that our analysis shows us that for the same population, having the same 'value system', for the same technology and the same products, the flow of goods in a given market can be both qualitatively and quantitatively different depending only on the 'history' of the system. Thus the fundamental diagram of 'supply' and 'demand' (fig.(16)) is misleading because it can only be constructed in re trospect. It refers to a particular outçome, and the intersection could have been elsewhere. Our model shows us that the 'free market' is not equally open to all agents, since the possibility of successful implantation on an existing market depends on the size of initial investment that can be made.

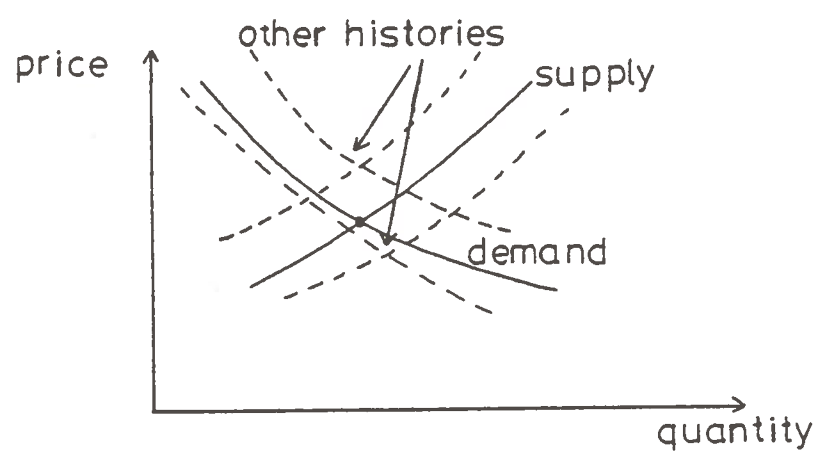


Fig.(16).

Also we see that under some slow change in the parameters of the system (e.g. market size, or economies of scale current interest rates) then a relatively sudden re-organization of the pattern of the consumption could occur when the previous one become unstable. In such changes, relatively small differences of possibly random origin or new initiatives (fluctuations) would prove decisive in the forging of a new structure. Our image of a market system is therefore that of a dynamic 'game' with a varying number of players and stakes, where periods of 'adaptive' jockeying are separated by successive 'crises' or periods of major reorganisation (Day, 1980).

If we consider the long term evolution of our market system then ofcourse the effects of 'innovations' will be of great importance. In general these innovations will occur insome sense, around existing dimensions and structures, causing the system and the 'values' of the population to evolve into new directions, so that societies with different histories will exhibit not only different socio-economic patterns but also in the long run,different 'value systems'. For example, in western society, the automobile was considered simply as an amusing luxury only some 40 or 50 years ago, but the evolution of the system as a whole has led to the fact that it is now viewed as a basic necessity for millions. Similarly, it seems clear from this point of view that the impact of one society on another is a complex and dangerous phenomena, involving a clash of values which the market does not necessarily 'translate' in a neutral manner. Ofcourse, it remains true that the 'market' system does nevertheless involve an exploration of the potential demand among the population for different goods (although it may be imperfect) while this is not necessarily the case for a 'planned economy'. For such a complex system as this there is probably no simple answer to the problem of how the economy should 'best' be run, but then why should there be ?

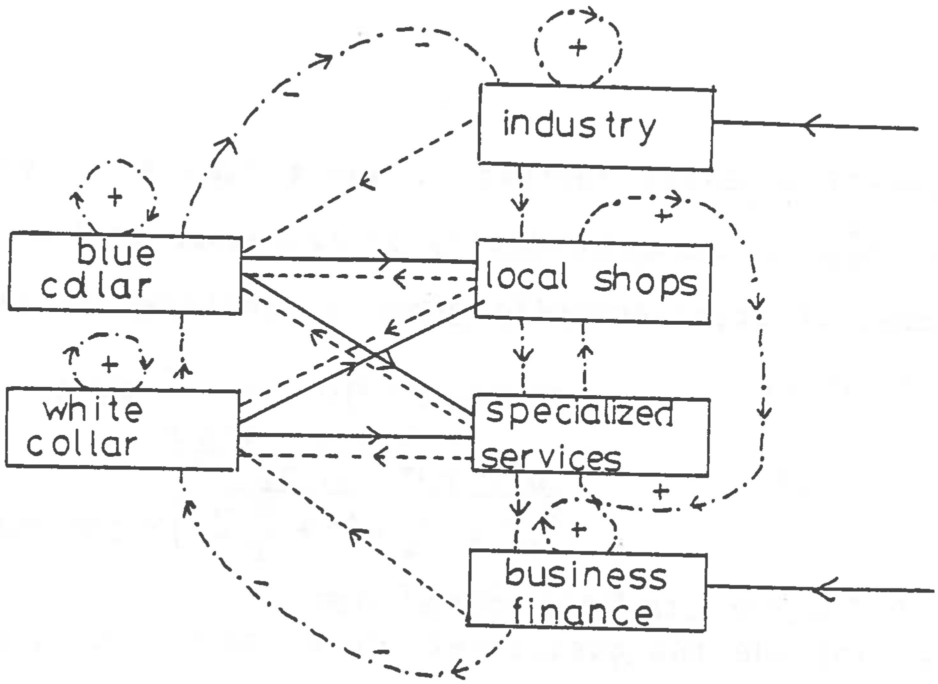
All these points and difficulties are raised clearly when for example, we apply the methods of analysis outlined above to study the evolution of a market in its two spatial dimensions. Recently, urban evolution has been considered from this point of view. We shall not give the details here but simply describe the important points concerning this evolution, which our paradigm of self-organization reveals.

3. THE EVOLUTION OF URBAN STRUCTURES

The urbanization of a region can be studied as economic functions are introduced at different point in the system, and either find a sufficient market and grow, or are eliminated by the competition. The structure that emerges depends on the timing and location of the launching of each economic function, as is therefore merely one of many 'possible' structures which are compatible with the equations representing the economic interactions. It is through the action of elements not explicitly contained in those equations (fluctuations and historical 'accidents') that the choices are in fact made at the various bifurcation points which occur during the evolution of the system. Thus the spatial organization of a region does not result uniquely and necessarily from the 'economic and social laws' enshrined in the equations, but also represents a 'memory' of particular specific deviations from average behaviour. This has been described in detail elsewhere (Allen and Sanglier, 1979), and we shall turn instead to the question of the evolution of urban structure within a city (Allen, Boon and Sanglier, 1980).

In agreement with much previous work, particularly for example the philosophy of a Lowry type model, first we consider the basic sector of employment for the city, and in particular two radically different components of this, the industrial base and the business and financial employment. Next we consider the service employment generated by the population of the city, and by the basic sectors, supposing two levels, a short range set of functions and a long range set. The residents of the city, depending on their type of employment etc. will exhibit a range of socio-economic behaviour, and for this we have supposed two populations corresponding essentially to 'blue' and 'white' collar workers.

The next phase of the modellng is in attempting to construct the interaction mechanisms of these variables, which requires as we have discussed, knowledge of the values and preferences of the different types of actors represented by the variables, and ofcourse how these values conflict and reinforce each other as the system evolves. In fig.(17) we show the basic interaction scheme for six variables whose mutual interaction leads, we suppose, to many of the important features of spatial structure. These variables reflect the decisions, particularly locational decisions, of six basic types of actor.



——→—— Demand for Goods and Services

----→-- Demand of Labour

-·—·→·- Cooperative effects, (economies of scale, common infra-structure, learning, etc.)

Fig.(17) The interaction scheme of our simple City system. -

We then construct our kinetic equations as in the previous section expressing the evolution of each variable, in each locality. As an example, let us write explicitly,

$$\frac{dx_i^k}{dt} = a x_i^k \left(\sum_j J_j^k \cdot \frac{A_{ij}}{\sum_{i'} A_{i'j}} - x_i^k \right) \qquad (9)$$

which expresses how the number of residents of socio-economic group k, at the point i, x_i, k change in time by the residential decisions of the sum of all those employed in the different possible sectors m, whose jobs are located at j. Thus, A_{ij}^{k} is the attractivity of residence at i as viewed by someone of socio-economic group k, employed in sector m at the point j.

cooperativity ... distance

$$A_{ij}^{k} = \frac{\nu^{k}(1+\sigma^{k}x_{i}^{k})\, e^{-b^{k}\Delta_{ij}}}{\left(\nu^{k}+\sum_{k}x_{i}^{k}+\sum_{L}J_{i}^{L}\right)} \leftarrow \text{crowding} \qquad (10)$$

$\nu^{k}, \sigma^{k}, b^{k}$ = characteristic constants

These include the considerations of cost and time in travel to work, the price of land, pollution and noise levels etc., as well as the character of the neighbourhood.

We have written down similar equations for the other actors, which in brief express, for example, the need for industrial employment to be located at a point with good access to the outside, and for a large area of job, as well as some 85% of their workforce being taken to be in the lower socio-economic group. We have also added the fact that the interdependence of many industrial activities leads to a preference for locations adjacent to established industrial locations. This term also covers many subtle effects of the infrastructure that grows around existing situations. The main effects are all noted on the interaction scheme of figure (17).

Here we shall briefly describe some of the simulations that we have made using our simple model. In the first case, we have looked at the evolution of a centre, which initially is only a small town, but throughout the simulation, due to population growth and expanding external demand from the industrial and financial sectors the town grows, spreading and sprawling in space as it does, and also developing an internal structure.

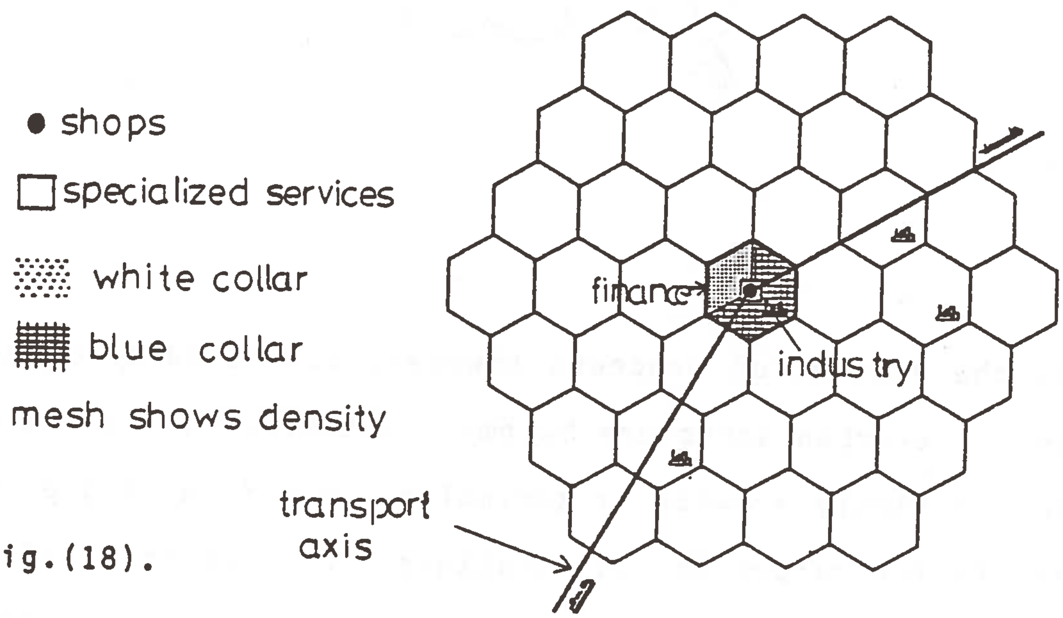


Fig.(18).

The initial condition of the simulation is shown in fig.(18). After 10 units of time, the sitution has evolved to that shown in fig.(19), where already, an internal structure has appeared. Industry, commercial and financial employment are all still located at the centre, but now we observe residential decentralization, particularly on the part of the upper socio-economic group. The centre is very densely occupied and is strongly 'blue collar'.

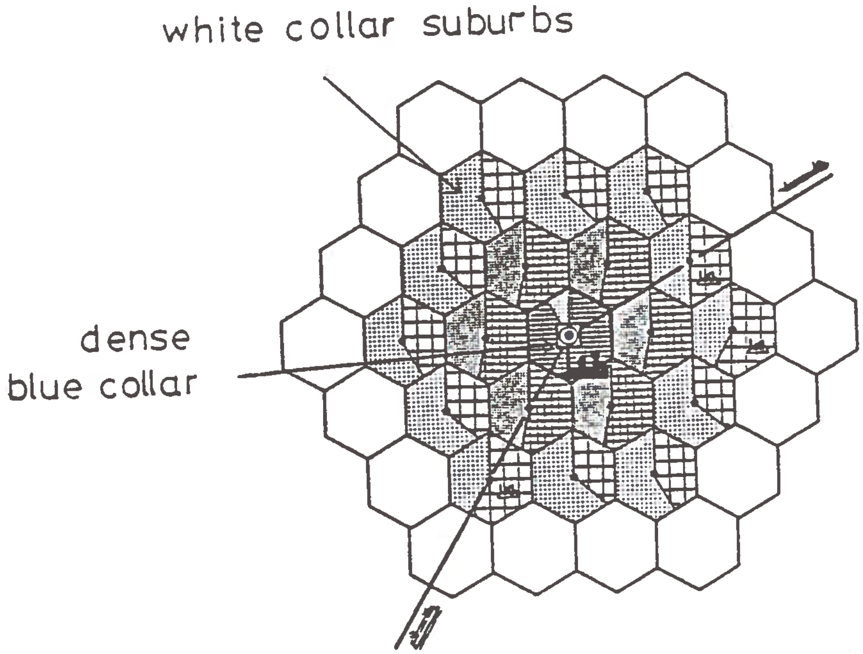


Fig.(19)

As the simulation proceeds however, at around 15 units of time, this urban structure becomes unstable. It is not a question of simply growing of shrinking, what is at issue is the qualitative nature of the structure. For, at this point in time, the very dense occupation of the centre is beginning to make industrial managers think about some new behaviour. For some of them the cost of continuing to operate in the centre, is making them contemplate the abandonment of the infrastructure and mutual dependencies that have grown up with time. At this point, as for a dissipative structure, it is the fluctuations which are going to be vital in deciding how the structure will evolve. At some point there is an initiative, when some brave (if it works out, stupid if it doesn't) individual decides to take his chance and to try to relocate at some point in the periphery. Where exactly, will depend on his particular perceived needs and opportunities. However, what is important is that whereas, before this time such an initiative would have been 'punished' by being less competitive, now, around t = 15, the opposite is true. Once the nucleus is started, and ofcourse its own infrastructure begins to be installed, so almost all the industrial activities decentralize, and establish themselves in this new position in the periphery.

At this point, many different initiatives could succed in carrying the system off to some particular new state of organization. However, those which succeed with the least effort are the industrial nuclei in the periphery, lying along the communication axis.

From this point on, however, the locational decisions of the 'blue collar' workers are particularly affectd by the fact that their value systems are now based on the fact that industrial employment has re-located in the south-western corner of the city. Thus, the spatial distribution of blue collar residents in the city starts to change, having in a sense a new focus. This inturn acts on the locational choices of the white collar workers, who find space easily in the regions of the city less favoured by the blue collars, and whose spatial distribution adjusts accordingly. Changes in the distribution of local service employment also then occur, and the whole structure evolves to the pattern shown in fig.(23) by time t = 40. Here, we see that we have actually displaced the centre of gravity of the urban centre, and have an urban structure which ressembles two overlapping urban centres of different character. In the south west we have predominantly working class, industrial satellite, whi-le, the original city centre is a C.B.D. and important shopping and commercial district, with predominantly white collar suburbs stretching away from it on three sides. In this part of the city, it is the second ring that has attracted the local shopping centres, while in the industrial satellite, it is the heavily populated, industrial district itself that has become an important shopping centre. From our simulation we can calculate traffic patterns, travel distances and energy costs and we find a complicated behaviour for these.

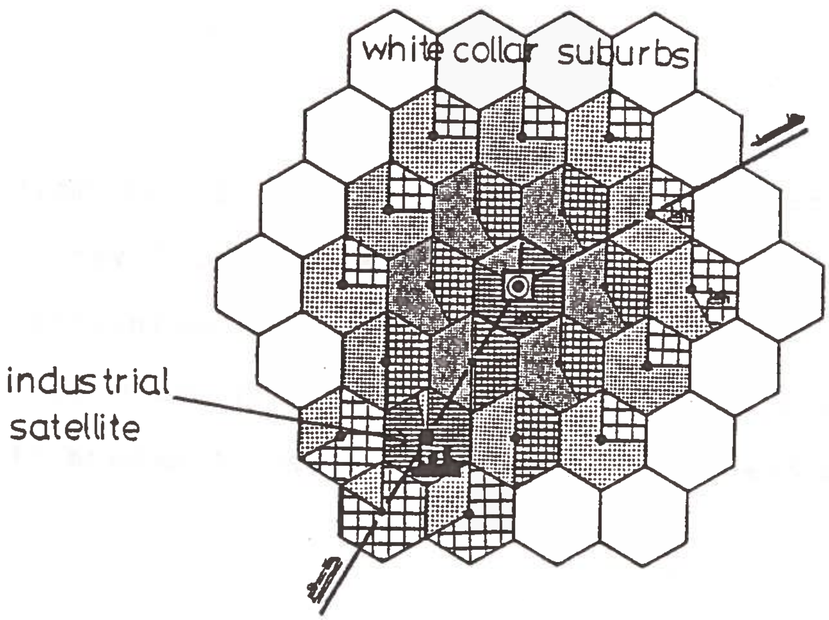


Fig.(19). By time t=40 , the urban structure has changed qualitatively from that of fig.(9). It has developed a second focus, and has structured functionally. That is, one centre is essentially an industrial stellite, while the traditional centre has become largely a CBD and the important shopping centre. We may also note that in the traditional centre, the retail employment has moved outwards to the second ring, (suburban shopping centres), while in the industrial centre the retail employment is still centralized.

This shows us the dangers involved in global modelling, for on that scale, what we see is an apparently inexplicable change in behaviour, in which the distance travelled per person, and the average energy consumption per person stops rising and even decreases. Only a model which can describe the internal restructuration of the city could have predicted such a change, and linear systems theory, and input-out-put flow models would have to be re-calibrated at this point. In other words, relationships between global variables of complex systems nearly always involve non-linearity and a systems analysis which assumes linearity will only be reasonable in the short term, or in a neighbourhood of the calibration.

CONCLUSIONS

One of the most important points that arises from our discussion and simulations concerns the level of explanation which is aimed at by a model. If we approach a complex system with a desire to model it so that we may understand its evolution and direct our policies more rationally, then clearly, we must first set up what we consider to be the 'structure' of our system. However, if this structure simply reflects the 'structure/function' present in the system at the initial moment, and we then calibrate the 'model' on this initial state, then any 'prediction' that the model makes assumes that the function and structure do not change. This may be quite wrong. Our point of view, derived from the concepts underlying dissipative structure, is that the initial structure/function of the system (pattern of consumption, or where different popultions and jobs are located/traffic flows between them) is itself the result of an evolutionary process which, after a particular history involving both macroscopic and microscopic factors, was established in the system. Because of the existence of multiple solutions, in fact the dynamic equations of the macroscopic variables (the 'model') are ambiguous and could have given rise to 'other' structures if the particular history has been different. Thus, if we admit that the particular initial structure/function of the system with which we start is a 'special case', and that micro factors outside the model led to its establishment, then we must also admit that this will be true of the future evolution. In other words, the future will also have its 'historical accidents' when we look back on it, and although the importance of such events is often widely accepted as concerns the past of a system, modellers have in general not seen the implication for the future.

In order to build models which can cope with such problems, we must therefore look for the underlying interaction processes which can give rise to the many different structure/functions that are observed for different circumstances and histories. The basis of such a search must be human behaviour, outside of explicit statements about space. Thus, the 'structure' of the model should not explicitly contain spatial structure, but this should result from interactions of the humans in the system as they make choices according to their value systems and constraints, choices which arise because of particular initiatives by other actors in the system following the same program but viewed from a difffe-rent place, and role in society. Part of the choices is indeed that relating to the evolution of the numbers of individuals in each role, and the invention of new roles.

If we look at our interaction diagram for the intra-urban, then we see that this type of approach is indeed initially non-spatial. Thus the interaction cheme could perfectly well exist with identical values of variables at each point of the system. It is, potentially, totally symmetrical. However, because of fluctuations, both in the 'real world' and in the 'mental maps' of individuals, can explore situations which are 'richer' than reduced description of the world which is a model, so this symmetry can be broken, and having been broken can be amplified if some actors perceive an advantage in the new behaviour, and have the 'power' necessary to adopt it. Thus evolution is always characterized by events in which 'abnormal behaviour' becomes 'normal behaviour', when 'informal structure' becomes 'formal'. Small fluctuation are amplified by the advantages perceived by at least some of the actors. Even if such advantages correspond to disadvantages for other actors, then it would depend on the 'power' or 'leverage' of the opposing groups as to whether or not the changes would take place.

Clearly decision is related to perception and by manipulating information one can change the evolution of the system. Both direct advertiring and propaganda as well as social pressure in the form of fads and fashions can create desires and frustrations which may mark the system permanently. Values, it seems, are not the simple, self-evident certainties which we may have believed. Even such 'sure-fire' values a maternal love have recently been shown to be subtle and changing. What must face is that almost all our everyday actions are not the expression of an absolute rationality, but the result of a dynamic dialogue between 'system' and 'values', between 'supply' and 'demand', during which bifurcations occur. Their rationality is simply conferred on them by the society in which they are thought 'normal', where they have evolved, and they can, and will, change. The problem of policy making in a world with changing values is indeed a fundamental one. If we are to ever be able to understand such an evolution, then our models must not simply say : the system is organized like this. They must also examine the question, why is it like this ? The reply will involve necessarily an understanding of the reasons for its stability, and this in turn will allow an appreciation of its potential instability, and of the new dimensions and levels of organization that be created (Jantsch, 1980).

Summarizing the main points made above then, we have examined the behavioural basis of our models and shown how a more systematic inclusion of multiple criteria (both quantitative and qualitative) can be put into the equations. An important general point that arises is that a structural reorganization of say the urban space, leads to a corresponding reorganization of the mental maps and values of the various actors. The symmetry breaking properties of non-linear systems lead to a corresponding expansion of the dimensions of the actors value space. For example, in the case of an initially circular city, the variables and parameters of decisional criteria can all be expressed in terms of the scalar distance from the centre. Once the circular symmetry is broken, however, the value space expands to include all the angle dependent possibilities. Similarly, when all cars where black, the question or value attached to colour was of no importance. Once the symmetry had been broken, however, and cars of other colours appeared, then a new dimension is created in the value space of buyers and finally can become an important factor in sales.

Complexification feeds on itself because it creates new situations and dimensions, which widen the experience of people and create new tastes and qualities, leading to new behaviours and to further complexification and to the creation and destruction of patterns and organizations. Only a much more profound understanding of such self-organization, whose complex nature is merely glimpsed in the above, can help us steer a course in such an unfolding universe of self-discovery.

ACKNOWLEDGMENT

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TRANSPORTATION MODE CHOICE

David Kahn, J.L. Deneubourg and A. de Palma

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Milwaukee, Wisconsin
November 17-19, 1980

ABSTRACT

This paper presents a dynamic model of transportation mode choice and evolution of public transportation service based on some simple assumptions of individual behavior and economic necessities for providing transportation service. Critical values are shown to exist for the fares charged, for the cost of providing service, for the demand and supply of transportation (and for other parameters) at which the system will bifurcate to different possible states of the system; critical thresholds must be reached in the quality of the network to observe its growth. Also shown is the role of history and the role that fluctuations in individual behavior and mode strategy play in the way the system structures, that is, in the evolution of the relative number of users of each mode and in the level of service obtained.

I. INTRODUCTION

In a previous paper (Deneubourg, de Palma and Kahn, 1979), hereafter referred to as I, we developed a model of transportation mode choice of two variables, the number of people who choose the automobile and the number of people who choose public transportation. That model showed clearly how the system structures in response to individual behavior and showed the role that fluctuations play on the response of the system when different mode choices are made. However, the model did not take account of transportation costs and service.

In this paper, we extend the previous model by taking into account the service offered by the public transportation mode which is assumed to be a function of the number of users of the mode, of the fares charged by the mode, and of the costs of offering the service. By so doing, we shall find here the occurrence of an optimum level of service which is related to the fares charged. We also find the occurrence of critical values for the fares, for the cost of maintaining a level of service, for the demand for transportation, and for the publicity and strength of imitative behavior which will be chosen as bifurcation parameters for the evolution of the system.

As in the previous paper, I, we make no pretense at developing a model of transportation mode choice which captures all the decisions which go into such mode choices. The intention, rather, is to show how some decisions by individuals and by the public transportation company interact in a dynamic system and how fluctuations can lead to different evolutionary paths.

We may point out that a parallel approach has been developed by A. G. Wilson in the framework of catastrophe theory (Wilson, 1979).

II. THE MODEL

As in I, we make certain assumptions on individual behavior (or, more precisely, on the average behavior of a group of individuals) and through the non-linearities in this behavior we shall find how the system structures when thresholds for bifurcation are reached.

The system consists of three variables, the number of automobile users, x, the number of public transportation users, y, and the public transportation mode characterized by the global level of service it offers, L (this could be the number of buses, for example). We assume that an important determinant for individuals to choose the automobile is its speed (in a forthcoming paper we shall also take into account the convenience of the automobile expressed by its ubiquitous connectivity). We also consider that imitative behavior (or, in general, any behavior by which the presence of users increases the number of users) plays a role for such mode choice. Both determinants, the speed and the imitative behavior are functions of x, themselves.

For the public transportation mode which, to be specific, is taken to be the bus (though we could take the subway, with however a different scale for the parameters), we assume that the service offered and fares charged affect its usage, imitative behavior plays a role, and as a policy variable, we also assume bus usage may be affected by publicity or advertisement.

We express the above assumptions on mode choice in the dynamical equations for the evolution of x, y and L, of which the first two are given by (see I, Equation 6):

$$\dot{x} = \frac{DA_x}{A_x + A_y} - x; \quad \dot{y} = \frac{DA_y}{A_x + A_y} - y \tag{1}$$

where $\dot{x}$, $\dot{y}$ are the time rates of change of x and y, respectively. D is the demand for transportation which is assumed to be so slowly varying compared to the time variation of x and y that it may be considered as constant. That is to say, no new users are brought into the system during the time of interest. A_x is the attractivity for the automobile which we take to be its speed. We include the imitative behavior of people in this term, as well. A_y is the attractivity for the bus which will involve the service offered by the bus mode, the fares charged, the amount of advertisement for bus usage and also the imitative behavior of individuals.

The rationale of these dynamical equations is fully explained in I, and we only note here that $\dot{x} + \dot{y} = D - (x + y)$, so that in the steady state we have $D = x + y$.

The third equation to complete our system is for the evolution of bus service and is assumed to be given by:

$$\dot{L} = \nu y - KL \tag{2}$$

where ν is the fare charged (and thus νy is the revenue received) and K is the maintenance cost per unit of service offered. The equation simply states that bus service will grow in time if revenues exceed the cost of providing service.

It now remains to give explicit representations to the attractivities, A_x and A_y in Equation (1). For the automobile attractivity function, A_x, we assume as in I:

$$A_x = v_x \alpha_1 x \tag{3}$$

where v_x is the automobile speed and α_1 measures the strength of the imitative term $\alpha_1 x$. Also, as in I, we take the speed to be an inverse function of x (congestion effect see Haight, 1963; R. Herman and I. Prigogine, 1979), and neglect the traffic interaction between cars and buses:

$$v_x = \frac{1}{a + bx} \tag{4}$$

where a and b are positive constants.

For the bus attractivity, A_y,[1] we take the form

$$A_y = \frac{L}{\nu^2}(\theta + \alpha_2 y) \tag{5}$$

which states that the attractivity is proportional to the service offered, L, the publicity or information, θ (assumed positive) and the importance of imitative behavior measured by $\alpha_2 y$, and inversely proportional to the second power of the fares, ν, charged. We note that the form used for the dependence of A_y on the various parameters will affect the structure of the system (because of the dependence of the structure on the non-linearities). However, as it is not our intention here to reproduce an experimental result, and only to show how the system structures when non-linearities are present, we present these non-linearities

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[1]In (I), the attractivity for bus usage was given as proportional to the number of users, y, the idea being that the more users, the more frequent would be the bus service and hence the shorter the waiting time. Here we take the attractivity directly proportional to the quality of service, L.

(dependence of A_y on the parameters) as only reasonable possibilities. Though, we should point out that it is not difficult to alter these dependencies when sufficiently valid data justifies this.

If we further simplify the problem as in I by taking a = 0, b = 1 in Equation (4) which is equivalent to assuming a constant attractivity for the car, we obtain as our system of dynamical equations

$$\dot{x} = \frac{D\alpha_1}{\alpha_1 + \frac{L}{\nu^2}(\theta + \alpha_2 y)} - x$$

$$\dot{y} = \frac{\frac{DL}{\nu^2}(\theta + \alpha_2 y)}{\alpha_1 + \frac{L}{\nu^2}(\theta + \alpha_2 y)} - y \qquad (6)$$

$$\dot{L} = \nu y - KL$$

This system may be solved analytically. One stationary state ($\dot{x}$ = o, $\dot{y}$ = o, $\dot{L}$ = o) of the system is

$$x = D, \; y = o, \; L = o \qquad (7)$$

which states that the total demand for transportation is provided by the automobile.

When we perform a stability analysis, subjecting system (6) to perturbations δx, δy, δL (see the Appendix for the details of this analysis), we find that the stationary state given by (7) is stable only when the costs, K, for providing bus service, are above a certain critical value K_c

$$K > K_c = \frac{D\theta}{\nu\alpha_1} \tag{8a}$$

since then there is no incentive for instituting bus service; or if the fares ν charged are above a critical value ν_c

$$\nu > \nu_c = \frac{D\theta}{\alpha_1 K} \tag{8b}$$

which represents the maximum fare people are willing to pay for the bus. The system (7) will also be stable if the demand for transportation, D, is below a certain critical value, D_c,

$$D < D_c = \frac{\nu\alpha_1 K}{\theta} \tag{8c}$$

since an insufficient demand does not justify the initiation of bus service. We also find that the all car system (7) is stable when the imitative behavior for car usage, α_1, is above a critical value, α_{1c} ,

$$\alpha_1 > \alpha_{1c} = \frac{D\theta}{\nu K} \tag{8d}$$

or the advertisement for bus usage, θ , is below a threshold θ_c ,

$$\theta < \theta_c = \frac{\nu\alpha_1 K}{D} \tag{8e}$$

In addition to the stationary state given by Equation (7), we find two other possible stationary states of the system (6), given by

$$y^{\pm} = \frac{1}{2}\left(D - \frac{\theta}{\alpha_2}\right) \pm \frac{1}{2}\sqrt{\left(D + \frac{\theta}{\alpha_2}\right)^2 - 4\frac{\alpha_1 \nu K}{\alpha_2}}$$

$$x^{\mp} = \frac{1}{2}\left(D + \frac{\theta}{\alpha_2}\right) \mp \sqrt{\left(D + \frac{\theta}{\alpha_2}\right)^2 - 4\frac{\alpha_1 \nu K}{\alpha_2}} \qquad (9)$$

$$L^{\pm} = \nu y^{\pm} / K$$

The stability analysis (see the Appendix) shows that when these solutions are real positive, the (x^-, y+, L+) solution is stable and the (x+, y-, L^-)solution is unstable. The implications of this for causing transitions between stable states will be seen in the next section when we discuss the results of a numerical example.

The solution (9) will be real (positive or negative) if the cost K for providing bus service is below a critical value K^c:

$$K < K^c = \frac{\alpha_2 (D + \theta/\alpha_2)^2}{4\alpha_1 \nu} \qquad (10a)$$

Both solutions will exist physically if $K > K_c = \frac{D\theta}{\alpha_1 \nu}$ (see Equation (8a)) and $D > \theta/\alpha_2$. If $K < K_c$ with $D > \theta/\alpha_2$ only the stable solution (x-y+, L+) will be positive (will exist physically). This is illustrated in the schematic.

Similarly, the solution (9) will be real if the fares ν are less than a critical value ν^c

$$\nu < \nu^c = \frac{\alpha_2 (D + \theta/\alpha_2)^2}{4\alpha_1 K} \tag{10b}$$

and will be positive if $\nu > \nu_c = D\theta/\alpha_1 K$ and $D > \theta/\alpha_2$. When $\nu < \nu_c$ only the stable solution will physically exist.

In terms of the demand for transportation, D, the condition that the solution (9) be real is that there be a sufficient demand D^c,

$$D > D^c = \sqrt{4\alpha_1 \nu K/\alpha_2} - \theta/\alpha_2 \tag{10c}$$

and when the demand $D > \theta/\alpha_2$ but less than $D_c = \alpha_1 \nu K/\theta$, both solutions will exist. If $D > D_c$ only the stable solution will be positive..

In terms of imitative behavior for the car, α_1, there will be two real roots when

$$\alpha_1 < \alpha_1^c = \alpha_2 (D + \theta/\alpha_2)^2 / 4\nu K \tag{10d}$$

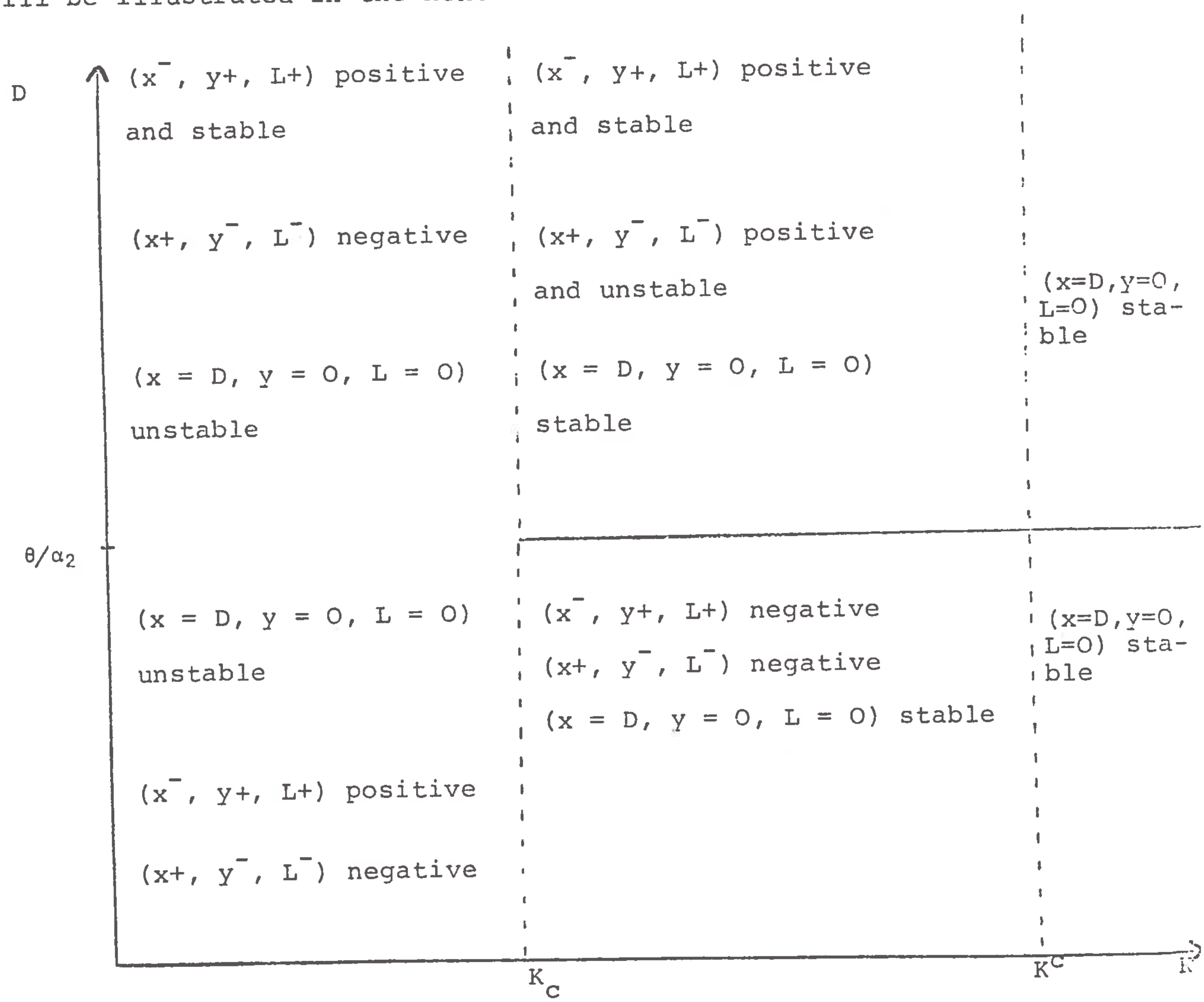
with both roots positive when $D > \theta/\alpha_2$ and $\alpha_1 > \alpha_{1c} = D\theta/\nu K$ and one positive and one negative root when $D > \theta/\alpha_2$ but $\alpha_1 < \alpha_{1c}$.

Finally, in terms of the bus publicity term θ, there will be two real roots when

$$\theta > \theta^c = \sqrt{4\alpha_1 \alpha_2 \nu K} - \alpha_2 D \tag{10e}$$

with both roots positive when $\theta < D/\alpha_2$ and $\theta < \theta_c = \alpha_1 \nu K/D$, and only one positive root if $\theta > \theta_c$.

These conditions, in terms of parameter K, are summarized in the schematic. The implications of this kind of system structure will be illustrated in the next section with a numerical example.



SCHEMATIC SHOWING DIFFERENT REGIONS FOR STABILITY AND SIGN OF ROOTS.

III. DISCUSSION OF A NUMERICAL EXAMPLE

In this section we discuss the structure of the system as a function of the parameters of the system. The numerical values of the parameters are given in the figures.

A. Fares

Figure 1 shows the three variables of the system, the number of people choosing the car mode, x, the number choosing the bus, y, and the service offered by the bus mode, L, as a function of increasing fares ν charged by the bus company.

As fares increase but remain below a critical value only one stable stationary state is possible, the $(x^-, y+, L+)$ state. The other stationary state $(x = D, y = 0, L = 0)$ exists but is unstable in this low fare regime, so that any perturbation from this state, no matter how slight, will cause the system to jump to the stable state (and we note that in the real world perturbations always are occurring). In this regime, the number of bus users decrease (because of the increasing fares), the bus service improves (because of increasing revenues) and the number of automobile users increases (corresponding to the decrease in the number of bus users).

As fares continue to increase beyond ν_c, but still remain below ν^c, two stable stationary states exist and one unstable stationary state exists in the system. In the stable $(x^-, y+, L+)$ state the number of bus users continues to decline with increasing fares, and there is a corresponding increase in the number of car users. Bus service continues to improve with increasing fares but then reaches a maximum and begins to rapidly deteriorate because the increasing fares being charged cannot make up for the resultant loss of passengers.

Figure 1 - MODE CHOICE AND QUALITY OF SERVICE VERSUS FARES

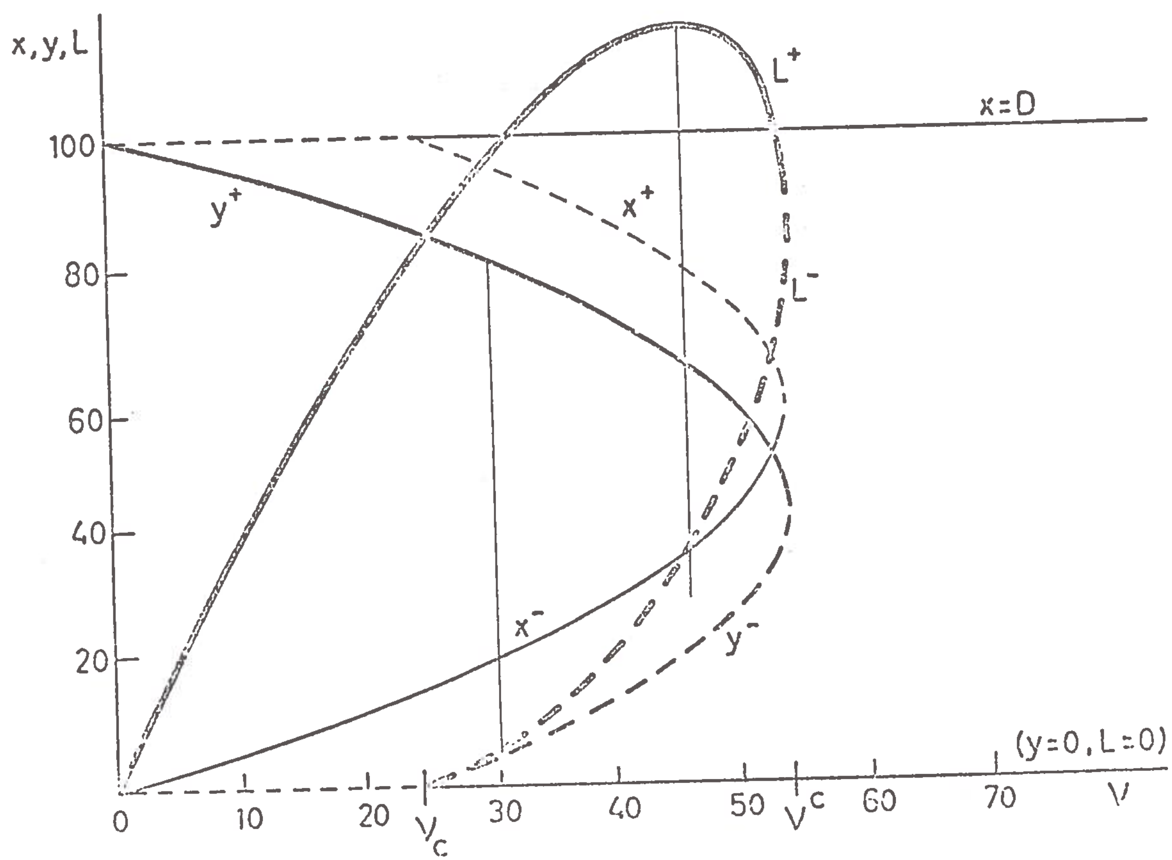
Solid lines: stable stationary state

Dashed lines: unstable stationary state

Parameter values: $\alpha_1 = 5$, $\alpha_2 = 30$, $\theta = 30$, $K = 25$,

$D = 100$

Critical values: $\nu_c = 24$, $\nu^c = 52.9$



The optimum fare ν_m that should be charged for the best service may be computed analytically. This is most easily done by first finding the optimum number of passengers for producing maximum service. This is obtained from

$$\frac{\partial L}{\partial y} = \frac{\nu}{K} + \frac{y}{K}\frac{\partial \nu}{\partial y} = 0 \tag{11}$$

We obtain for the optimum number y_m

$$y_m = \frac{1}{3}\left[D - \frac{\theta}{\alpha_2} + \sqrt{\left(D - \frac{\theta}{\alpha_2}\right)^2 + \frac{3D\theta}{\alpha_2}}\right] \tag{12}$$

The optimum fare ν_m is then given by

$$\nu_m = \frac{\alpha_2}{\alpha_1 K}\left[\frac{D\theta}{\alpha_2} + y_m\left(D - \frac{\theta}{\alpha_2}\right) - y_m^2\right] \tag{13}$$

where we have used Equation (9) to obtain ν as a function of y. We also note that (11) may be put into the form $\frac{dy}{y} \,/\, \frac{d\nu}{\nu} = -1$ which shows that the maximum L is achieved when the elasticity is -1.

We now point out the consequences of this kind of structure of two stable stationary states and one unstable state on the response of the system to fluctuations.

As the fares continue to increase in this regime $\nu_c < \nu < \nu^c$, it becomes more and more likely that a fluctuation in the number of car or of the number of bus users will be found that will cause the system to jump to the zero bus users state.

Finally, for still higher fares ν exceeding the critical value ν^c, the system becomes insensitive to perturbations, adopting the ($x = D$, $y = 0$, $L = 0$) stationary state which is stable in this regime of high fares $\nu > \nu^c$.

B. COST OF PROVIDING SERVICE

Figure 2 shows the bifurcation diagram as a function of costs of providing services K.

When the costs are below the critical value K_c, there is one stable stationary state in which buses and cars co-exist. The all-car solution is unstable in this regime of low costs.

As might be expected, the level of bus service decreases with increasing costs,[1] and hence the number of bus users decreases with a corresponding increase in car users.

As costs continue to rise, in the range $K_c < K < K^c$, the system can exist in one of two possible stable stationary states. If the system is in the $(x^-, y+, L+)$ state, the chances of remaining there diminish with increasing costs, as the strength of a perturbation which could cause the system to jump to the $(x = D, y = 0, L = 0)$ state decreases with increasing costs.

When costs exceed the critical value K^c, no one chooses the bus and only the $(x = D, y = 0, L = 0)$ stationary state is stable.

C. PUBLICITY FOR THE BUS

Figure 3 shows the relationship between x, y and L and the amount of publicity or advertisement for bus usage.

The system has one stable stationary state below a critical value θ^c, two stable stationary states in the range $\theta^c < \theta < \theta_c$ and one stable stationary state for θ beyond θ_c. The figure points to the need to exceed a critical value θ^c before people will choose the bus mode, but once this critical value is exceeded, further publicity has very little effect on increasing ridership.

[1] Because of the form of the steady state solution $L = \nu y/K$, we obtain a rather unrealistic result for very low costs, $K \rightarrow 0$.

Figure 2 - MODE CHOICE AND QUALITY OF SERVICE VERSUS COSTS

Solid lines: stable stationary state

Dashed lines: unstable stationary state

Parameter values: $\alpha_1 = 5$, $\alpha_2 = 2$, $\theta = 30$, $\nu = 45$,

$D = 100$

Critical values: $K_c = 13.3$, $K^c = 29.4$

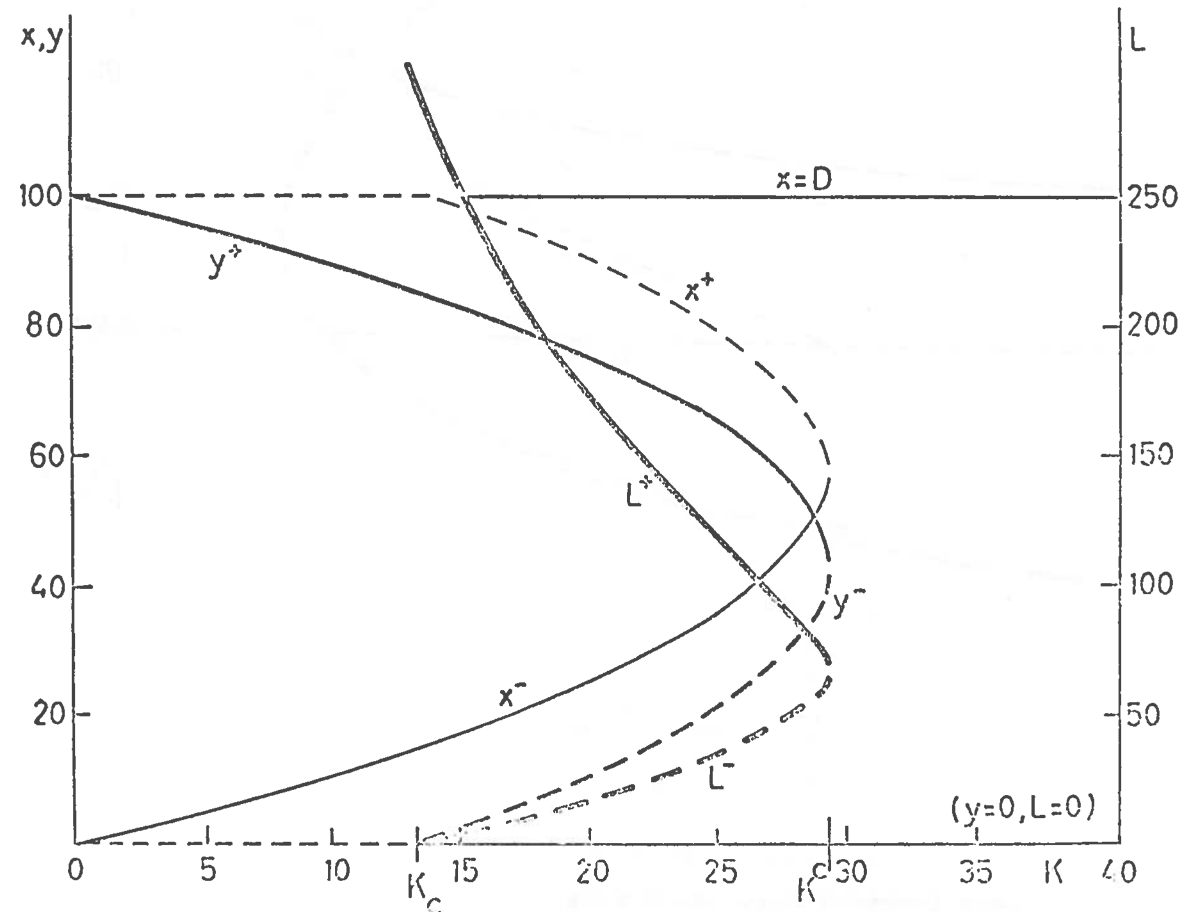


Figure 3 - MODE CHOICE AND QUALITY OF SERVICE VERSUS PUBLICITY

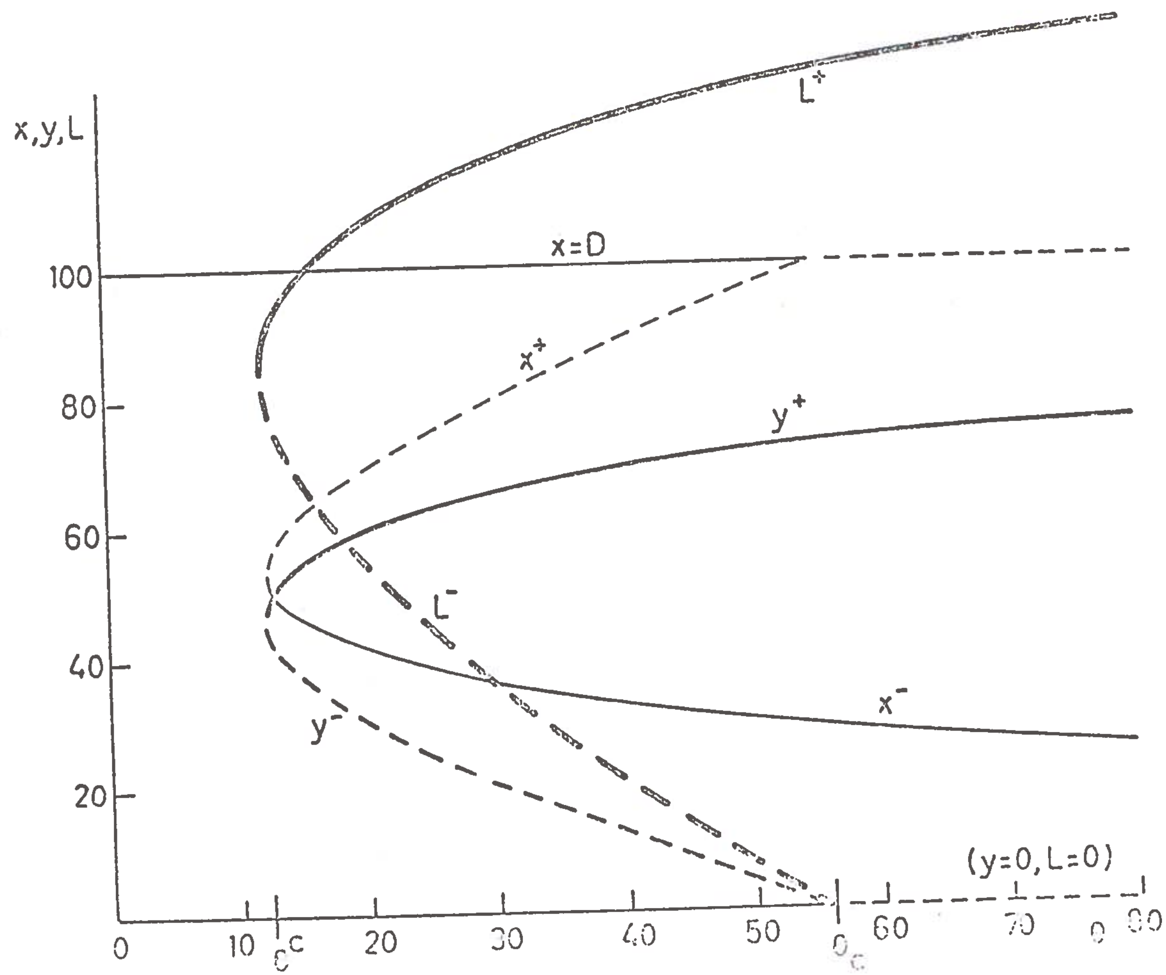
Solid lines: stable stationary state

Dashed lines: unstable stationary state

Parameter values: $\alpha_1 = 5$, $\alpha_2 = 2$, $\nu = 45$, $K = 25$, $D = 100$

Critical values: $\theta_c = 56.3$

$\theta^c = 12.1$



However, if the system happens to be in the all-car state, increasing publicity does have a strong effect on increasing the likelihood that a fluctuation will cause the system to change to the mixed mode state. And when $\theta > \theta_c$ any perturbation will cause the system to jump to the mixed mode state.

We remark here that once the publicity exceeds θ_c (so that any perturbation will cause the system to jump to the bus users state), it is not necessary to maintain the same high level of publicity for the system to remain in this state, as is evident from the figure. This is an example of the phenomenon of hysteresis.

D. DEMAND FOR TRANSPORTATION

Figure 4 shows the effect of total demand for transportation D on mode choice x and y and on bus service, L.

When there is an insufficient total demand for transportation, no bus service is offered. Not until a critical value of demand D^c is exceeded is bus service offered. The zero bus state, however, is still a possible stable stationary state in the range of demand $D^c < D < D_c$ but becomes increasingly less likely because smaller and smaller fluctuations can cause the system to jump to the mixed mode solution.

For still higher demand, $D > D_c$, the zero bus users state becomes unstable. In the stable stationary state, the number of car users declines with increasing demand as congestion effects become more pronounced, the number of bus users increases as people leave their cars, and bus service improves as more revenues are received because of the increased bus usage.

E. IMITATIVE TERMS

Figure 5 shows the bifurcation diagram as a function of the strength α_1, of the imitative behavior for car usage.

Below a critical strength α_{1c}, the mixed mode solution is the only stable stationary state in which car usage, as expected, increases with increasing α_1.

In the range $\alpha_{1c} < \alpha_1 < \alpha_1^c$, the all-car mode solution also becomes a stable state and when $\alpha_1 > \alpha_1^c$, the all-car mode becomes the only possible stationary state of the system.

Figure 6 shows the effects of the strength α_2 of imitative behavior for bus use on mode choice.

Below a critical value α_2^c only one solution is possible, namely, the all-car state; not until sufficiently strong imitative behavior for bus usage exists do people choose the bus mode.

With increasing strength of imitative behavior for the bus, $\alpha_2 > \alpha_2^c$, two solutions become possible -- the all-car state and the mixed mode state. While, in this case, the all-car state remains a stable stationary state, it becomes less and less likely that the system, if in this state, will remain there because as α_2 becomes stronger only small positive fluctuations in the number of bus users or in the bus service are needed to cause the system to move from the all-car state to the mixed mode state.

F. TRAJECTORIES

The different situations discussed in the previous paragraphs are depicted in (L,Y) phase space to help visualize trajectories in the three qualitatively different situations which can occur.

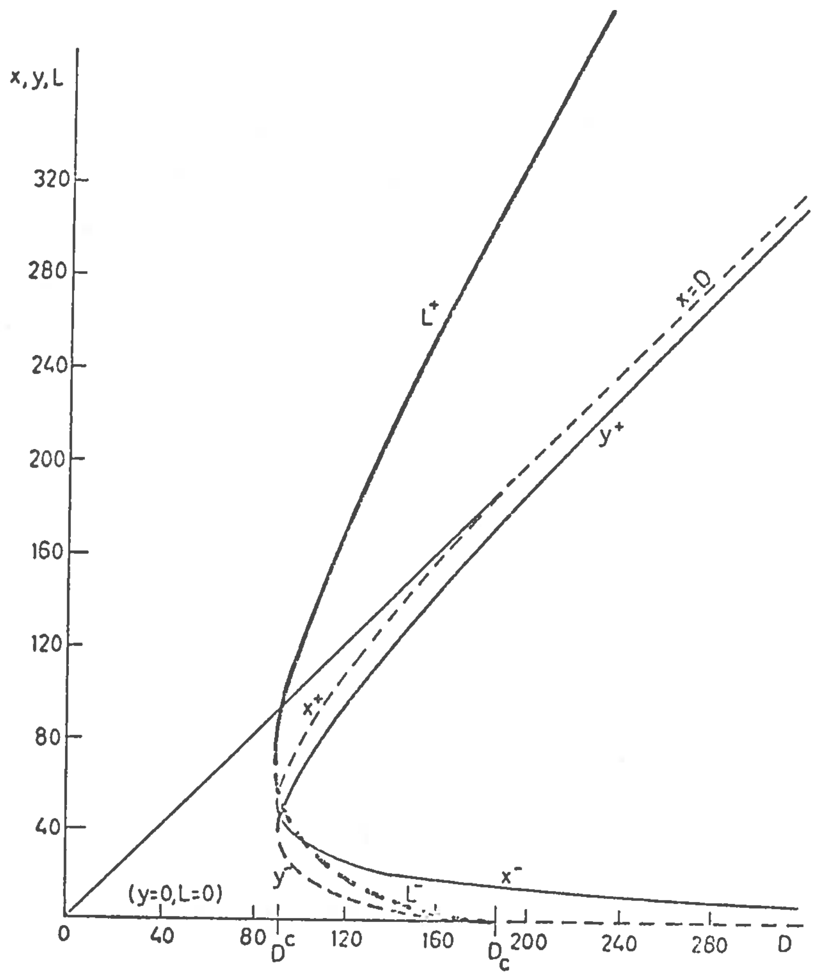


Figure 4 - MODE CHOICE AND QUALITY OF SERVICE VERSUS TOTAL DEMAND FOR TRANSPORTATION

Solid lines: stable stationary state

Dashed lines: unstable stationary state

Parameter values: $\alpha_1 = 5$, $\alpha_2 = 2$, $\nu = 45$, $K = 25$, $\theta = 30$

Critical values: $D_c = 187.5$, $D^c = 91.1$

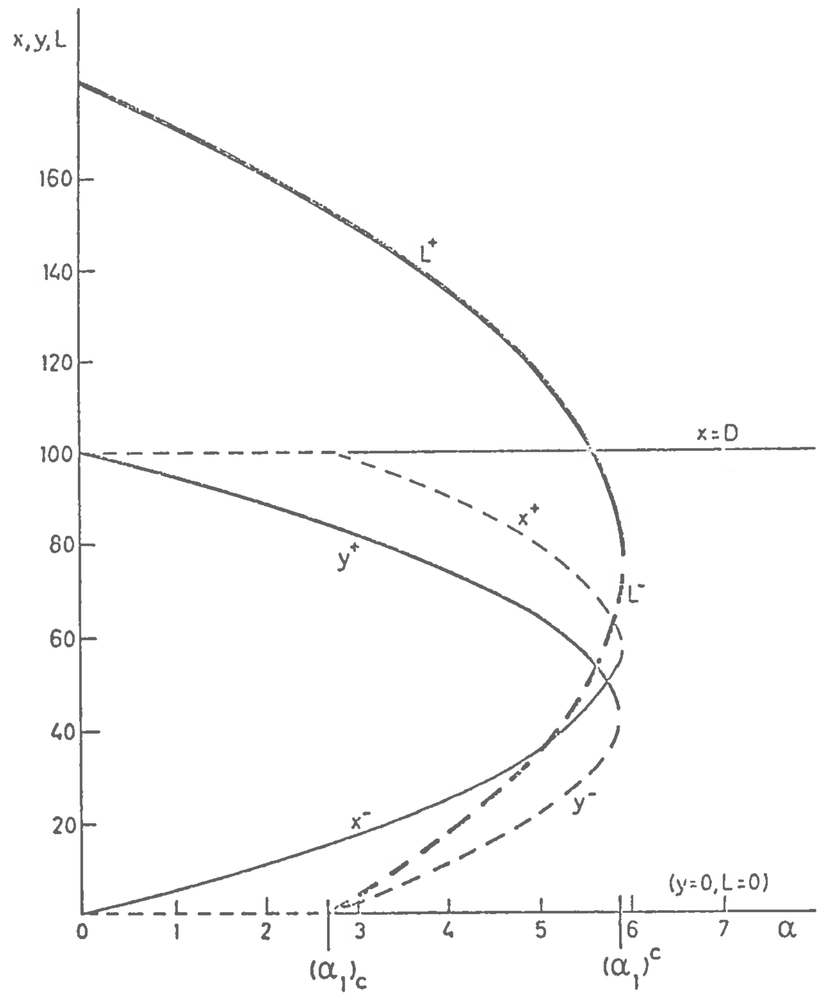


Figure 5 - MODE CHOICE AND QUALITY OF SERVICE VERSUS IMITATIVE BEHAVIOR FOR CAR USAGE

Solid lines: stable stationary state

Dashed lines: unstable stationary state

Parameter values: $\alpha_2 = 2$, $0 = 30$, $\nu = 45$, $K = 25$, $D = 100$

Critical values: $\alpha_{1_c} = 2.7$, $\alpha_1^c = 5.9$

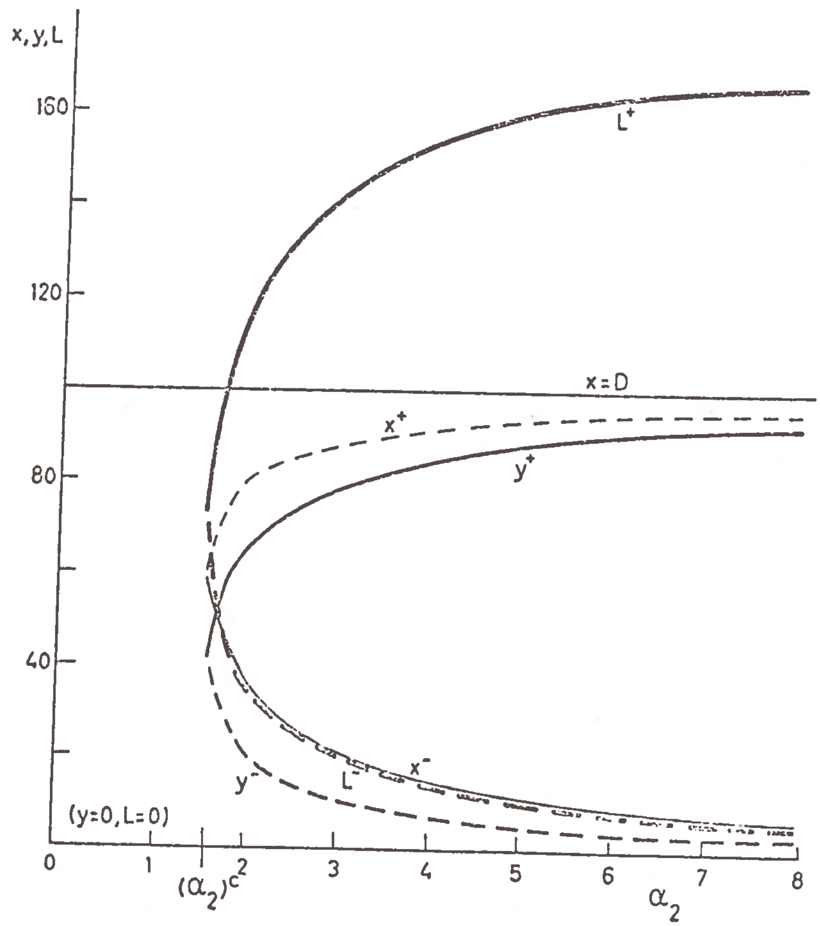


Figure 6 - MODE CHOICE AND QUALITY OF SERVICE VERSUS IMITATIVE BEHAVIOR FOR PUBLIC TRANSPORTATION

Solid lines: stable stationary state

Dashed lines: unstable stationary state

Parameter values: $\alpha_1 = 5$, $\theta = 30$, $\nu = 45$, $K = 25$, $D = 100$

Critical values: $\alpha_2{}^c = 1.6$

Figure 7 depicts the situation when there is one stable node at (0,0); Figure 8 shows the case when there is one stable node at (0,0) and two non-trivial stationary states: a stable node (x^-, y+, L+) and a saddle point (x+, y^-, L^-); and Figure 9 depicts the situation when there is a saddle point (0,0) and a non-trivial stable node (x^-, y+, L+). We note that the non-trivial stationary states lie on the line $y = \frac{k}{\nu} L$.

In the case of Figure 7, all trajectories converge to the stable node (0,0) so that once the system reaches this stationary state, it loses all memory of perturbations and of its initial state.

In the situation of Figure 8, we have drawn the separatix, S, which separates two regions, labeled I and II. A point in region II is within the "sphere of influence" of the stable node (0,0): whatever the initial conditions in this region, the system will evolve to the stable node (0,0).

If, however, the system is in the (0,0) stationary state, a critical size perturbation which will bring the system beyond the separatix into region I is necessary to reach the non-trivial stationary state (x^-, y+, L+).

We remark that this says a critical size investment in public transport is necessary to bring the system away from the "all" car situation; below that critical value, the investment is lost.

Figure 9 may be considered as a limiting case of Figure 8: in Figure 9 whatever the size of the perturbation from (0,0), the system will evolve to the non-trivial stationary state (x^-, y+, L+).

IV. CONCLUSIONS

In this paper we have presented a dynamic model of transportation mode choice in which mode choice was based on individual behavioral characteristics and on the service offered by the mode.

In examining the stationary states of the system and the stability of these states to fluctuations, we found the existence of critical values of the parameters (fares charged, cost of providing service, demand for transportation, etc.) at which the system bifurcated to a new solution.

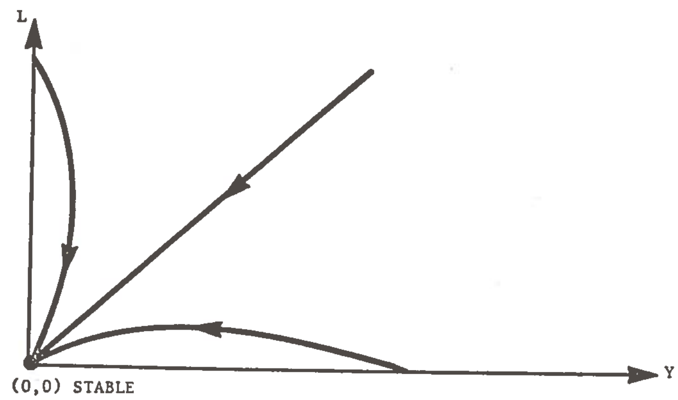
For some range of the parameters we found that only one of two possible states of the system was stable to fluctuations and hence in this range the system would adopt one of the two possible states (the stable one).

In another range of values of the parameters we found the existence of two stable states separated by an unstable one. This kind of structure, in which two stable states exist, points to the role of history (through the initial states and through fluctuations) in determining which state the system will adopt (since either one is theoretically possible).

Further, this kind of structure also points to the importance of fluctuations in influencing the behavior of a system as sufficiently strong fluctuations can cause the system to jump from one stable state to another. The size of the fluctuation needed depended on the closeness of the unstable state to one of the stable ones which, in turn, depended upon the values of the parameters of the system.

We point out that the concept of self-organization which appears under certain conditions involving the feedback between a system and its environment, springs from the work done in

Figure 7 - Trajectories in (L,y) Phase Space. One stable node at (0,0).



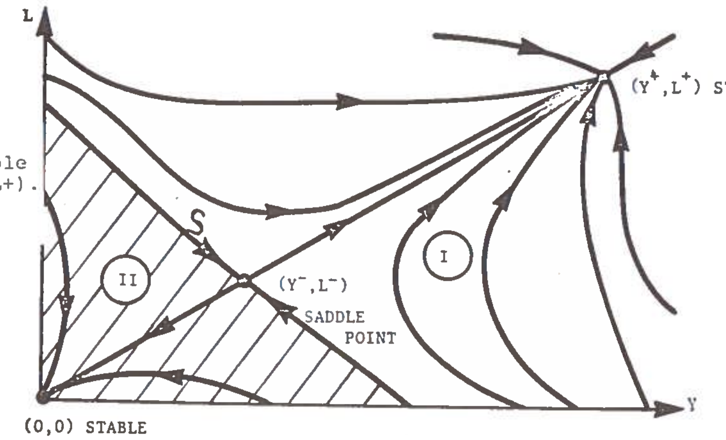


Figure 8 -

Trajectories in (L,y) Phase Space. One stable node at (0,0) and one stable node (x^-, y+, L+). One saddle point (x+, y^-, L^-).

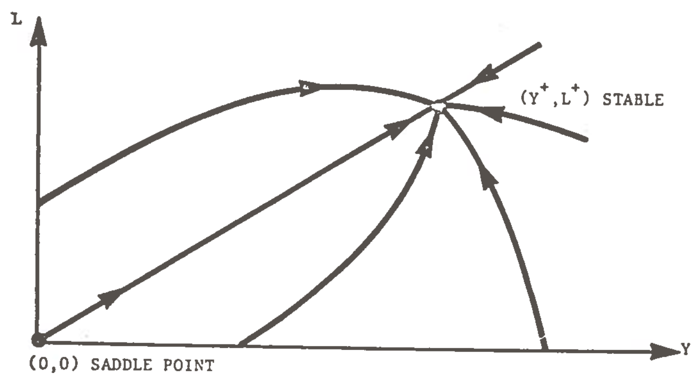


Figure 9 - Trajectories in (L,y) Phase Space. One saddle point at (0,0) and one stable node (x^-, y+, L+).

non-linear thermodynamics (Nicolis, Prigogine 1977) and has found specific applications in biology, ecology and the social sciences.

APPENDIX

STABILITY ANALYSIS

The dynamical equations of our system are (see section 2)

$$\dot{x} = \frac{D\alpha_1}{\alpha_1 + \frac{L}{\nu^2}(\theta + \alpha_2 y)} - x$$

$$\dot{y} = \frac{\frac{DL}{\nu^2}(\theta + \alpha_2 y)}{\alpha_1 + \frac{L}{\nu^2}(\theta + \alpha_2 y)} - y \qquad \text{(A-1)}$$

$$\dot{L} = \nu y - KL$$

We do a linear stability analysis, subjecting this system to perturbations δx, δy and δL around a stationary state. We assume the variables to have a time dependence of the form $e^{\omega t}$. The stability of the stationary state will depend upon the sign of the real part of ω: if $\omega > 0$ the system will amplify the fluctuation and hence be unstable to fluctuations; if $\omega < 0$ the fluctuations are damped and the system is stable to the fluctuation.

The resulting set of equations when we only consider the case $\delta x = -\delta y$ are:

$$(\omega + 1)\,\delta y = \frac{\frac{D\alpha_1}{\nu^2}\left[(\theta + \alpha_2 y)\,\delta L + \alpha_2 L\,\delta y\right]}{\left(\alpha_1 + \frac{\theta L}{\nu^2} + \frac{\alpha_2 y L}{\nu^2}\right)^2} \tag{A-2}$$

$$(\omega + K)\,\delta L = \nu\,\delta y$$

One stationary state of system (A-1) is given by ($x = D$, $y = 0$, $L = 0$). In this case, Equations (A-2) reduce to

$$(\omega + 1)\,\delta y = \frac{D\theta}{\alpha_1 \nu^2}\,\delta L$$

$$(\omega + K)\,\delta L = \nu\,\delta y \tag{A-3}$$

When these are solved simultaneously, we find as the equation for ω

$$\omega^2 + \omega(K + 1) + K - \frac{D\theta}{\nu\alpha_1} = 0 \tag{A-4}$$

Hence we find that the stationary state ($x = D$, $y = 0$, $L = 0$) is a stable node if

$$K > \frac{D\theta}{\nu\alpha_1} \tag{A-5a}$$

and a saddle point if

$$K < \frac{D\theta}{\nu\alpha_1} \tag{A-5b}$$

as given in Equation (8a) of section 2. This same stability relationship gives the conditions of stability in terms of the other parameters of the system (see Equations 8b - 8e).

The stability of the other stationary states is obtained in a similar manner, they are the solutions of

$$-y^2 + y\left(D - \frac{\theta}{\alpha_2}\right) + \frac{D\theta}{\alpha_2} - \frac{\alpha_1 \nu K}{\alpha_2} = 0 \qquad \text{(A-6)}$$

$$x = D - y$$

$$L = \nu y / K$$

The solutions (x^-, $y+$, $L+$) and (x^+, y^-, L^-) are given in Equations (9).

Solving Equations (A-2) simultaneously gives as the equation for ω

$$\omega^2 + \omega\left[K + 1 - \frac{\alpha_1 \alpha_2 D y}{\nu K \left(\alpha_1 + \frac{\theta y}{\nu K} + \frac{\alpha_2 y^2}{\nu K}\right)^2}\right]$$

$$+ K - \frac{D \alpha_1 (\theta + 2\alpha_2 y)}{\nu \left(\alpha_1 + \frac{\theta y}{\nu K} + \frac{\alpha_2 y^2}{\nu K}\right)^2} = 0 \qquad \text{(A-7)}$$

For positive values of the parameters, the stationary state given by $(x^-, y+, L+)$ of Equations (9) is a stable node ($\omega < 0$) while the stationary state $(x+, y^-, L^-)$ is a saddle point whenever the variables x, y, L are positive.

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ADAPTIVE ECONOMICS AND THE DYNAMICS OF URBAN-REGIONAL DEVELOPMENT

by

Richard H. Day
Department of Economics
University of Southern California
University Park, Los Angeles 90007
and
Economic Dynamics, Inc.
3650 Malibu Vista Drive
Malibu, CA 90265

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ADAPTIVE ECONOMICS AND THE DYNAMICS OF URBAN-REGIONAL DEVELOPMENT

by

Richard H. Day*

> The true system, the real system, is our present construction of systematic thought itself... Robert M. Pirsig

1. A NEW PERSPECTIVE IN URBAN-REGIONAL MODELLING

The research program sponsored in recent years by the DOT/Transportation Systems Center has emphasized dynamic aspects of urban development, the endogenous evolution of new urban structure (self-organization), and the role of constraints on transportation choices, Allen et al [1979], Dendrinos [1980], Zahavi [1979]. This program has been based on the recognition that general urban and regional planning and specific government transportation policy require an improved understanding of the complex interplay of forces shaping the form and quality of urban life and governing the evolving relationships among various economic regions. Many of these forces are economic in nature, but since their illumination must clearly involve basic considerations of human behavior and organization, it would appear that the comparative static, equilibrium methodology of orthodox economics needs to be augmented by a broader framework that incorporates dynamic structure and dis-

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*University of Southern California and Economic Dynamics, Inc.

equilibrium behavior. Such a framework is provided by adaptive economic theory and models.

Adaptive economics involves the extension of economic theory to incorporate the point of view that economic decision-makers are "boundedly rational" (have imperfect information, limited foresight, finite cognitive powers, and changing preferences) and consequently can make plans that are only suboptimal or temporarily optimal. It stresses the implication that economic decisons are imperfectly coordinated so that transactions and behavior must evolve out of equilibrium. It represents economizing behavior as governed by various adaptive processes such as feedback control, behavioral rules, trial and error search, suboptimization with feedback and other sequential decision procedures. It emphasizes that the basic economic entities (firms, households, banks, government agencies) evolve: their activities, numbers, rules of behavior and organization develop in a complex process displaying various modes of change (growth, oscillations, decay), and that exhibit changing phases which represent distinct stages or epochs with distinct structural characteristics.

Although the economic concepts of individual optimality, market equilibrium and social efficiency are essential in the theoretical development and evaluation of adaptive economic models, attention is shifted from the traditional concern with desirable static or steady economic states to a new emphasis on obtaining an improved understanding of how economies work and how their development <u>over time</u> might be influenced by new policies governing behavior and organization.

The objectives of the present paper are:

(1) to review the main features of adaptive economics

(2) to review and illustrate the closely related; recursive programming modelling methodology;

(3) to summarize the general characteristics of model generated behavior;

(4) and to consider the implications of these characteritics for understanding economic development giving particular attention to "self-organization," the role of constraints in determining choices in urban systems, and the use of nonlinear dynamical system theory and related concepts of bifurcation, catastrophe, phase-change and chaos.

It is our hope that the present background paper will provide the starting point for the development of a general model of urban-regional dynamics that will provide a flexible tool for investigating such issues as urban decline and decay, suburbanization, urban revitalization, alternative energy uses, the effects of conservation and shortages on transportation development, industrial development and zoning, public capital development, and so on.

2. ADAPTIVE ECONOMICS

2.1 The Disequilibrium Niche Day [1980c]

Although dynamic analysis and the broader aspects of change and evolution have received major treatments at the hands of economists, and though a concern with development has been a central concern of the discipline since the classical period of Adam Smith, Malthus and Ricardo, the ruling paradigm is still that of an economy in general equilibrium: a situation in which agents optimize, all agents' plans are consistent (supply equals demand) and no agent can be made better off without making others worse off: there is no incentive to change at prevailing prices. This idea has been extended to the realm of dynamics by establishing the existence of intertemporal equilibria in which agents' plans are intertemporally optimal, intertemporally consistent and intertemporally efficient. The stationary state is replaced by a steady-state. The more extreme idea that the business cycle possesses these equilbrium properties has even come into vogue.

Corresponding to the prevailing equilibrium description of economic life is the method of comparative statics. This method is based on the comparison of equilibria that vary with parameters of the system. When these parameters correspond to government control variables (tax rates, subsidies, transfers schemes, expenditures) the comparison of equilibria becomes the primary tool of economic policy analysis. Implicit in this practice is the assumption that the more complex dynamic process, whose structure is not specified in the equilibirum model, is stable in the sense that when the equilibrium is perturbed the real system will begin moving toward and converge to the new equilibrium. The implication is that the past is like a "disturbance" to the new prevailing conditions whose influence will gradually diminish as a new equilibrium path becomes established and transient motion dies out.

The wide spread adherence by economists to the equilibrium approach is due in part to its compelling simplicity and elegance and in part to its undoubted success in explaining numerous historical and contemporary phenomenon. . Still, its extreme abstraction from experience and its inability to address a broad range of theoretical and practical problems has left a gaping intellectual niche that has yet to be filled. This niche is concerned with the study of economic systems when they are not in equilibrium. It is concerned with specifying the salient structural features and the implied dynamic behavior of disequilibrium systems.

Of course there has been activity in this niche. One would have to mention - in addition to our classical mentors - the historical and institutional economists, the business cycle theorists, the various simulation modellers, and among individual scientists, the great Joseph Schumpeter [1934], whose ideas constitute what William Baumol [1970] has called "the last grand dynamics." But none of these contributions has ever gained the momentum of a main stream and a central unifying theory has not emerged that would find a place for each.

In recent decades, however, a number of developments have taken place in various fields within and without economics that seem to make possible a new approach to dynamic, theory. This approach provides a synthesis of many old strands of thought, startling new insights into how economics work and how human society evolves. We will briefly consider here four specific developments, namely, behavioral economics, system dynamics, recursive programming, and evolutionary modelling. The synthesis of these developments constitutes what I call adaptive economics, Day [1975], following Simmon's [1957] use of the term "adaptive" to describe boundadly rational behavior and adjustment processes.

2.2 Behavioral Economics

The first strand of thinking really had its origins nearly half a century ago during the so-called marginal-cost pricing controversy. Someone had finally got around to asking business managers how they determined prices. It was discovered that most of them not only use some version of a mark-up formula but had not even heard of what economists had thought to be the rational way for businessmen to behave. You can imagine what this did for businessmen's reputations within the economics profession! But businessmen march to a different drummer. They actually pursue profit while facing the prospect of ruin. For various reasons they continued in their pursuit to use mark-up formulae, seemingly heedless of their standing amongst economists.

The controversy itself need not concern us here. Its list of contributors is already long enough. For us the significant thing is that it launched a new line of inquiry involving direct observation as a source of hypotheses about economic behavior. A comprehensive effort to establish a new economics based on observed patterns of behavioral regularity emerged in the so-called behavioral economics school founded by Herbert Simon [1957A] in his seminal work Administrative Behavior and developed in collaboration with him by James March, Richard Cyert, and various of their students, such as Oliver Williamson (see March and Simon [1958], Cyert and March [1963] and Williamson [1967]). The idea behind their approach was to observe how people behave, systemitize and formalize their rules of behavior and study the dynamics of models based on these rules using analysis and computer simulation. Although an impressive number of studies appeared using this approach, until very recently it has remained in the shadow cast by the ruling equilibrium paradigm. A recent surge of interest is no doubt explained in part by the Nobel prize awarded to Simon for his work in the area.

2.3 System Dynamics

While this new line of work was underway, a parallel development was launched when Jay Forrester decided to shift from a careeer as inventor and manager of large-scale engineering systems to a concern with scientific management. His conceptual approach, in effect, was the same as the behavioral school, but in its execution he developed an ingenious modelling language that allowed these rules to be programmed, documented and simulated within a single coherent system. The language itself, either in its visual, flow-charting form or in its computer dialect, followed a consistently formulated set of rules for rigorous dynamic modelling (Forrester [1961]).

For purposes of the present discussion the most significant features of this system dynamics approach are (1) its presumption that behavior is goal adaptive, using negative feedback, servomechanism type rules Forrester [1966]; (2) response to environmental changes often involves thresholds and discrete switching rules; (3) nonlinearities pervade economic systems.

The most significant properties of the solution of system dynamics models for purposes of our present discussion are (1) their capacity to change behavioral modes during the course of a computer run, perhaps exhibiting growth, oscillation and decay in turn; (2) their capacity to evolve through different systems of feedback loops in what may be called an endogenous shifts in structure; (3) their tendency to accumulate error, to be unstable with respect to small data changes so as to suggest that quantitative prediction is an inapprorpiate objective and that instead, qualitative understanding should be the proper objective in dynamic analysis.

2.4 Recursive Programming

Explicit economizing or optimizing behavior was demoted to a mere vestage in the behavioral economics and system dynamics schools just summarized. My own work on recursive programming models, which was begun in 1957 while I was still a graduate student, may be viewed as an effort to retain this model of behavior in its central place within the general structure of economic analysis while at the same time placing it in a dynamic, disequilibrium context with a primary objective of incorporating essential features of behavioral realism, Day [1963].

Recursive programing models are, formally, models that represent economizing as a sequence of recursively connected, "local," approximate or behaviorally conditioned optimizations or suboptimizations (Day and Cigno [1978] The recursiveness is provided in part by a feedback structure that represents the external environment just as in Bellman's dynamic programming or in conver tional optimal control models. But the optimizing is assumed to be performed without the complete knowledge by the agent being modelled of this external environment, so that an optimal strategy in the Bellman sense is not used to represent behavior. Instead, the economizing agent is represented as making more or less cautious departures from current operating conditions in the best direction according to current perception and approximation.

The solutions of recursive programming models share the essential features of system dynamics and behavioral simulation models: the evolution of qualitative mode, the shift in structure, sensitivity of trajectories to initial conditions. Of special interest here is that in RP models the shift in structure occurs as the systems of equated constraints selected by economizing switch so that different variables and different equations may govern the evolution of the system at different points in time. This in effect means that different feedback loops are involved. Each such structure is called a phase and a given model contains a (possibly very large) set of potential phases and phase sequences or phase evolutions. The result is not only an endogenous theory of modal change as in any nonlinear dynamic system *but an endogenous theory of structural evolution based on explicit economic trade-offs*.

2.5 Evolutionary Models

Although Alfred Marshall is remembered primarily for his exegesis of marginalist equilibrium relationships his famous text is dominated by biological analogies and explicit reference to competition and selection in an economic context. Firms compete for a market, vary their behavior at the margin and are selected on the basis of profitability. Losers go bankrupt and winners gradually approach a normal profit equilibrium. It is an evolutionary theory explicitly based on competition, variation and selection for "fitness" among members of a population. Although this Smith-Malthus-Darwin-concept of development has been told as a background story for justifying the equilibrium paradigm and the comparative static method (Alchian [1950]), it has seldom been incorporated explicitly in dynamic economic modelling.

In a seminal dissertation published in the Yale economic Essays in 1964 Sidney Winter chose this paradigm as the appropriate one for understanding how markets work. A series of papers co-authored with Richard Nelson has followed this line in studying specific evolutionary models, where a populations of technological alternatives can be selected or discarded on the basis of simple cost comparisons and according to rules of the type advocated by the behavioral school. Distributions of firms with differing cost structures emerge, but conventional equilibria need not come about. Again, computer simulations have been used extensively in the search for qualitative generalizations but Winter has shown that analytical results can be obtained as well. See Winter [1971] and Nelson and Winter [1978].

2.6 Adaptive Economics

These several developments in dynamic economic modelling share an explicit recognition of cognitive limitations, imperfect coordination and the need for buffers to mediate transactions out of equilibrium. They form a rich body of ingredients for a sysnthesis of economic and noneconomic thought, that may serve as a new general economic theory of change and evolution.

From the perspective of this adaptive economics, the path of economic development is viewed as a sequence of states, each member of which has evolved from its predecessor in response to the actions taken by the economic agents involved. The agents respond to their changing environment, taking into account their currently perceived constraints and objectives based on available information inherited from socio-economic and natural environment.

Their actions are based in part on rational plans, but influence the system through a feedback structure that is only partially understood and imperfectly accounted for in the planning process. Because decision-makers have imperfect information, limited foresight and changing preferences, they can make plans that are consistent and optimal only in a stationary equilibrium. In general the plans are imperfectly coordinated, and are based on expectations that are seldom fulfilled. They rarely lead to equilibria in which supply equals demand and technical and social efficiency prevail. Instead, plans are inconsistent among the various agents and actions must be based in part on adjustment procedures or behavioral rules that have worked satisfactorily in the past and which may be revised in response to new information. In addition special institutions and mechanisms must exist to mediate economic transactions that are out of equilibrium.

2.7 Disequilibrium Mechanisms

"Disequilibrium" institutions and mechanisms make it possible for the individual agents and.sectors to continue functioning when their plans cannot be fulfilled. Stores function as inventories on display mediating the flow of supplied and demanded commodities without the intervention of centralized coordination or of complicated and time-consuming market tatonnement procedures. Banks and other financial intermediaries regulate the flow of purchasing power among uncoordinated savers and investors, and mediate the flow of credits and debts that facilitate intertemporal exchanges without simultaneous bartering of goods. Ordering mechanisms with accompanying backlogs and variable delivery delays together with inventory fluctuations provide a flow of information that facilitate adjustment to disequilibria in commodity supplies and demands. Insurance and other transfer schemes such as unemployment compensation place resources in the hands of agents who would possess no admissible action without them.

The function which all of these (and many other mechanisms) perform is to allow the economy to exist in disequilibrium. Without them it could not. Economic society would breakdown and have to be reconstructed all over again. These agents of disequilibrium did not always exist. Barter and auctions were once used extensively and money consisted of "real" goods. If economies were in equilibrium none of these institutional inventions would have been required. And if primitive economies were essentially stable and evolved toward equilibria then the primitive disequilibrium mechanisms would have sufficed and withered away, gradually becoming obsolescent. Instead, new and more elaborate institutions have arisen. Just why that must be so will concern us below. At this point we can say that models of adapting economies will contain elements representing these and other devices allowing disequilibria to exist, thereby maintaining individual and organizational viability.

3. RECURSIVE PROGRAMMING MODELS

3.1 Basic Ideas

Recursive programming (RP) models are, as we have alread noted, adaptive processes that represent behavior or planning computations by sequences of recursively connected, local, approximate, or behaviorally conditioned suboptimizations. The recursive connection is determined by a feedback structure which usually is not completely accounted for in the specification of the optimizing operator. The latter property, which distinguishes recursive programming behavior from intertemporally optimal behavior is based on the fundamental premise that real world economic computation and behavior procede by decomposing large complex decision problems into smaller, simpler, approximate or local decision problems which are modified by feedback on the basis of behavioral rules, convenient computational formulae and observed changes in the decision-making environment. In short it is the theory of partial economizing or suboptimization with feedback that describes economic behavior in disequilibrium or temporary equilibrium. Recursive programming models incorporate rationality in the form of explicit optimizing but in a way that focusses on the central problem of adaptive economics, namely explaining how economizing takes place and how economies really work.

Data, Optimization and Feedback

From a purely formal point of view a recursive programming model is a three component system involving optimizing, data and feedback operators.

The optimizing operator describes the dependence of certain decision or choice variables on objective and constraint functions that in turn depend on various parameters or data. The data operator defines how the data entering objective and constraint functions depend on the current state of the system as a whole. The feedback operator specifies how the succeeding state of the system depends on the current optimal decision variables, the data and the current state. Given an initial state for the system the data for an optimization can be generated, the optimization problem formed and solved, and the next state of the system evolved through feedback. In this way a sequence of optimizations is generated in which the parameters upon which any one optimization are based depend on past optimizations and parameters in the sequence. The model is described schematically in Figure 1.

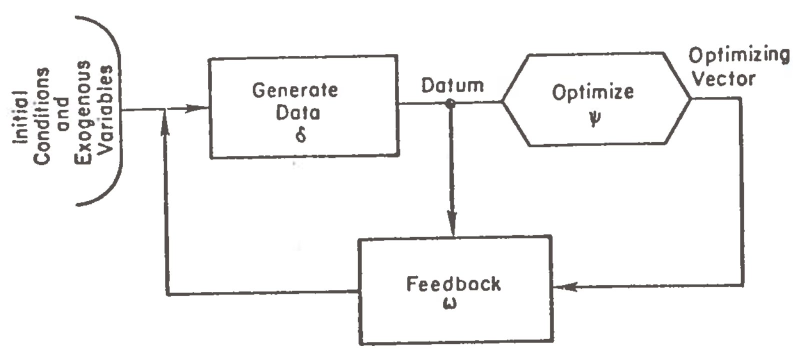


Figure 1. The Recursive Programming Model, Day and Cigno [1978, p.10].

It is essential to note that while each solution in the sequence of recursively generated optmizations satisfies certain optimality properties, the sequence as a whole need not and in general will not. Indeed some models with this structure can be constructed that will generate pessimal performance, just as other examples can be shown to generate optimal performance. The method can be contrasted with dynamic programming and optimal control theory by noting that in dynamic programming the optimizing operator is the fundamental variable to be determined. That is, given the feedback operator and an objective function that establishes a preference structure among trajectories, an optimal stratey is derived which will generate an optimal decision for any given state as it occurs. The sequence of decisions as a whole must satisfy an optimality principle, or in a system subject to stochastic shocks, the expected actons must satisfy such a principle. In optimal dual control both the data and optimizing operator are chosen to satisfy an optimality property. In recursive programming the optimizing and data operators are specified to obtain a closed dynamic system and the qualitative or quantitative behavior resulting from the model as a whole is then investigated. As the optimizing and data operators may not be an optimal strategy with respect to the feedback operator the sequence of optimizations need not satisfy the principle of optimality. This is why the terms "suboptimization with feedback" or "suboptimal control" may be used to describe this class of models.

3.2 Areas of Application

Although models of the kind under consideration here have not been generally thought of as a single coherent modelling approach, they have arisen in a wide variety of applications and have a long tradition within economic theory. Indeed they have arisen in at least three broad areas of study: (1) economic theory in which models are formulated and studied to obtain the logical implications of specific assumptions about economic behavior; (2) computational algorithms for static and dynamic optimization problems in which a complex optimization problem is decomposed into a sequence of simpler, approximate, or local optimization problems with feedback; and (3) economic simulation in which the behavior of an economic unit, or group of economic units is studied by computer simulation. These three areas will be briefly reviewed.

Theory of Economic Behavior

Recursive programming uses constrained maximizing to describe the plans or intended behavior of an economizing agent or group of agents, but with the added assumption that actual performance is determined by additional forces unaccounted for in the individual optimizations. These additional forces may act on the agent through environmental and behavioral feedback in the form of physical and financal accumulations (and decumulations), through information incorporated in estimates of current states and forecasts of anticipated states, through behavioral rules that make allowances for future decision making, that modify objectives on the basis of past behavior and that limit change from established behavior as a tactic for avoiding uncertainty.

Nonetheless, strategic considerations can be incorporated into an RP model. To do so the optimizing operator is given an optimal control or dynamic programming structure in which the payoff of an anticipated sequence of future actions is maximized subject to a simplified or approximate feedback operator (the perceived transition equation). A plan consisting of "optimal" intended future behavior is derived, or a strategy is derived which specifies "optimal" current behavior given current information. This "strategic" optimizing operator is imbedded in a model of the "complete" feedback structure. The RP model as a whole then represents an agent or several agents who are forward looking and whose plans have strategic quality, but whose actual behavior is conditioned by forces whose exact structure is not incorporated into their conception of the environment. In such a model the "true" optimal strategy is not used except by accident, or when learning is effective and true optimality is approached gradually with the passage of time.

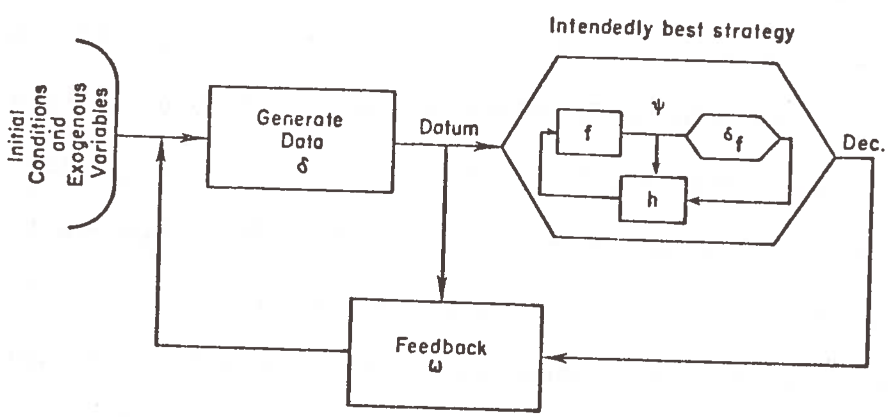


Figure 2. Recursive Strategic Programming Model of Intendedly Optimal Behavior (Rolling Plans or Planning Revision) Day and Cigno [1978, p.12].

An alternative way of using RP to describe behavior is to suppose that the center, or centers optimize with respect to the imminent period only, constrained (in addition to physical and technical constraints) by behavioral rules that provide for successive decisions and that afford protection from errors of estimation and forecasting. This description of a decision maker who proceeds according to a succession of behaviorally conditioned, suboptimizing, myopic decisions corresponds reasonably well to behavior observed in many business firms and government agencies. It is the basis for many empirical studies.

Planning Algorithms

The paradigm of a behaviorally conditioned, suboptimizing economic decision-maker is also a good description of certain algorithms for computing solutions to complicated planning models. Many of these algorithms are developed by decomposing the original problem into a simpler problem or set of simpler problems and a feedback rule that describes how the simple problems should be modified on the basis of past solutions, so that when they are solved by a known, convenient, economical method the solution will be closer than before to the optimum of the original complicated problem. One may think of the original complicated problem as an "environment", the simplified optimization problem as a decision maker's suboptimizing tactic, and the feedback rule as a means of using past decisions and feedback from the "environment" to obtain a new approximate decision problem. The sequence of suboptima should converge to the desired overall optimum, but in general, one can only approximate the desired solution in this way. The degree of approximation depends on the planner's computing budget and how efficient the algorithm is.

Sequences of local or approximate optimizations with feedback of the kind under consideration fall into two closely related categories. First is the case in which an optimization problem with complicated objective and/ or constraint functions is approximated by a problem with simpler objective and/or constraint functions. The general idea is illustrated in Figure 3.

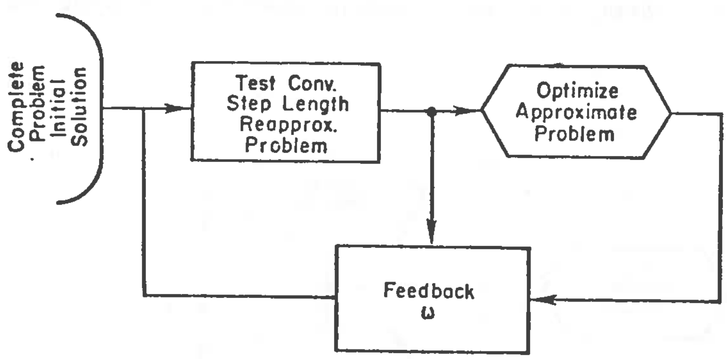


Figure 3. Approximate Optimization with Feedback. Day and Cigno [1978, p.3].

A formally similar application of this kind of algorithm is the interactive programming model. In this procedure the master problem is assumed to involve the unknown objective functions of a decision-maker and the known constraints to which his choices are subject. He is interviewed to determine directions of desired change from a trial solution. This is presumed to yield an approximate gradient of the unknown objective function. This is used as the basis for a suboptimizaton which yields a new trial solution. A new approximate gradient (by interview) is obtained at this point and the procedure repeated. If the decision-maker's preferences are "well-behaved" (that is, if they have certain appropriate mathematical characteristics), the iteration will converge to a best choice, which could not have been inituited.

The second class of examples, illustrated in Figure 4, involves decomposition algorithms and decentralized planning models. A problem of high

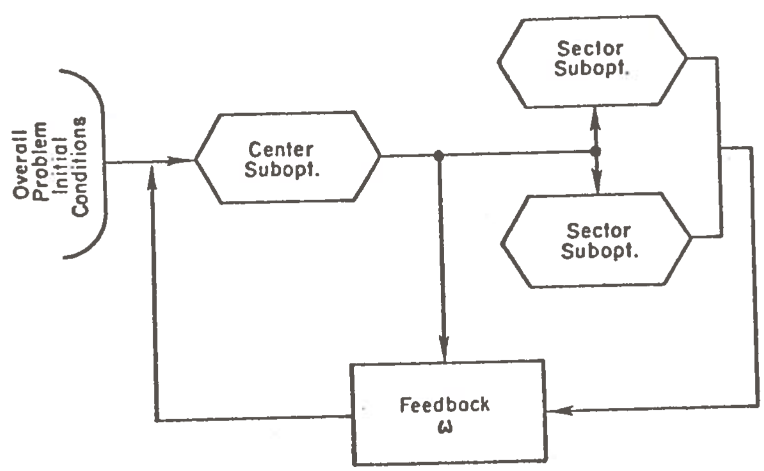


Figure 4. Decentralized Suboptimization with Feedback, Day and Cigno [1978, p.14].

dimension is decomposed into a set of decentralized, sector suboptimizations and a coordinating suboptimizations each of which is of much lower dimension and hence computationally less burdensome than the overall problem. The center passes initial data in terms of planning prices and/or budgets and quotas to the sectors who independently suboptimize their own situation given this information. Their solutions are then used by the center to form a central suboptimization from which is derived new information to be passed on to the decentralized sectors, and so on. The sequence of recursive optimizations then converge to the solution of the overall or joint optimum.

Behavioral Simulation Models

Recursive programming has been applied in various studies of dynamic behavior of firms, industries, sectors and national economies. Here we outline some of the behavioral hypotheses incorporated in these applied models.

The Adaptive Suboptimizing Tactic

The suboptimizing tactic uses a one-period optimization as the basis of choice without incorporating long-run trajectories based on an explicit representation of environmental feedback. The idea, based on direct observation of the way decisions are often made, is that decision-makers cope with considerable detail about their current situation and immediate future possibilities. They do not always consider longer-run developments. When they do, they often account for them in a rule-of-thumb manner by introducing constraints on current choice and modifying anticipated payoffs on short-run activities. Furthermore, they do not always, or even often, behave like statistically trained gamblers at Monte Carlo or Las Vegas on the basis of subjective probabilities about possible events according to Bayesian decision strategies. Rather, they respond to their best guesses about the possibilities with more or less caution. They constrain their departures from regions of familiar past behavior (experience) by rules-of-thumb. This hypothesis is called the principle of cautious optimizing. Day [1979].

Flexibility Constraints

One way in which the principle of cautious optimizing has been incorporated in recursive programming models is by introducing "flexibility constraints" into linear programming models of economic choice Day [1963], [1971]. These constrain choices for a single imminent period to lie within a zone of flexible response (ZFR) determined by upper and lower bounds on individual activity levels or linear combinations of activity levels. This in effect confines explicit economizing to a local search of alternatives in the neighborhood of current experience.

The flexibility constraints are recursively connected to past choices by behavioral feedback rules which give them a dynamic character. This dynamic character is brought out in Figure 5 which combines the phase diagramming technique for discrete dynamic processes with the feasible region for the one-period optimizations. The upper right quadrant of the diagram shows the ZFR for a given period's choice problem. The upper left and bottom right quadrants show how this ZFR is generated from past experience when the simple behavioral rule is used: "Do not increase or decrease a choice variable by more than a given percentage amount in any one period".

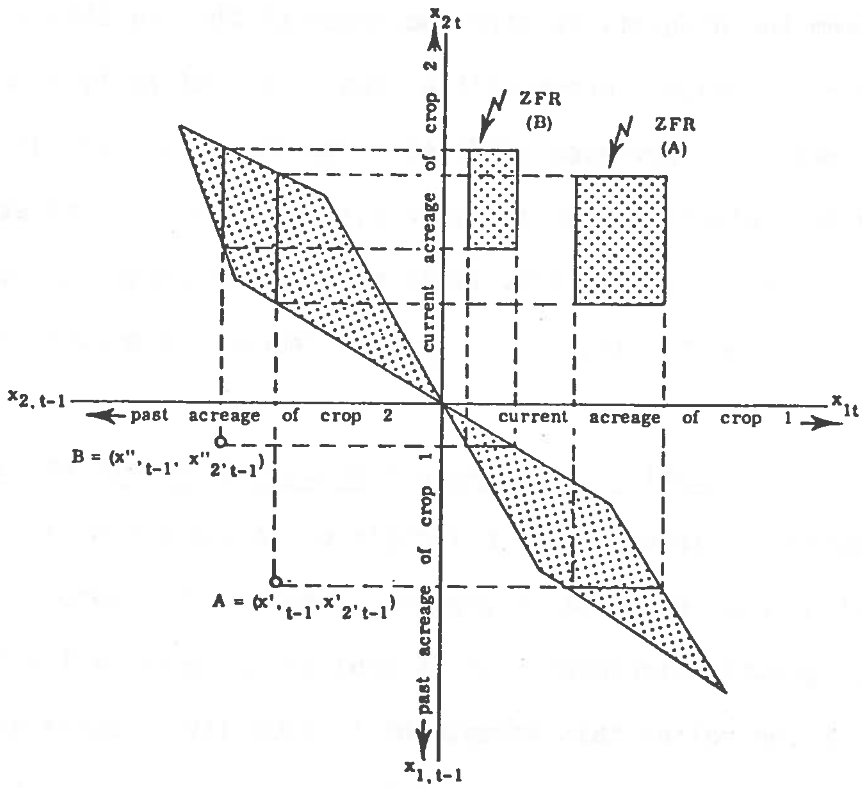


Figure 5. The Dependence of the Zone of Flexible Response on Experience

Source: Day and Singh (1977, p.83].

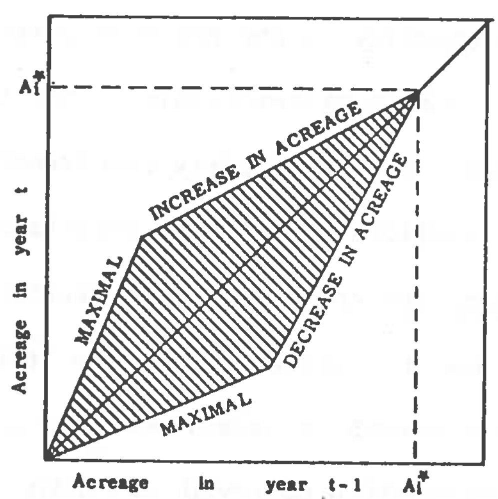


Figure 6. Region of Feasible Trajectories for a Given Crop

Source: Day and Singh (1977, p.82].

The immediately past choice is given in the lower left quadrant. As one can see from the diagram the size and shape of the ZFR changes once the actual choice is made. Consequently, the levels of activity possible in any given year are very much different from those possible in preceding years. The trajectory of all the activity levels must lie in a trapezoidal region as shown in Figure 6. Even fairly small percentage-change parameters ("flexibility coefficients") allow quite drastic changes to accumulate quickly.

Adjustments and Adoption: The Maximum Behavioral Growth of Capital Stock

A second way in which the principle of cautious suboptimizing has been incorporated into recursive programming models is by means of the "maximum behavioral growth principle". It is applied to investment activities and is based on the belief that investment in capacity is constrained by two essentially different behavioral considerations in addition to technical and economic considerations. The first is a resistance to adopting a new technique because of the time required to learn its use and perfect its application in existing firms. The second is the unwillingness to make decisions to expand capacity in any one year purely on considerations of capitalized values and cost differentials. This unwillingness occurs because of doubts about future capacity requirements and the possiblity of future, superior innovations. The first hypothesis is incorporated into a set of behavioral adoption contraints, the second into a set of behavioral adjustment constraints on investment activity levels. Together they place an upper bound on the growth in capacity of any given technique that leads to the diffusion curves often observed in studies of technological change. The adoption constraints have been given a simple form. The upper bound on investment in a given technique is proportional to the past period's capacity of that technique. The idea is that learning is proportional to exposure, and exposure is measured by existing capacity. These constraints are almost always equated in the early stages of adoption.

The investment adjustment constraints also place an upper bound on investment in a given period. They are based on the hypothesis, often used in other econometric models, that capacity is adjusted toward the current conception of the desirable capacity in the technique in question. In many of the RP models, desired capacity is taken to be proportional to the sales forecast of final commodities. Investment is constrained to be not more than some given proportion of the difference between this amount and current capacity.

The effect of these behavioral rules, coupled with an exponential depreciation rule (for example), is that the capital stock of any given capital good is constrained to follow a trajectory within a convex, trapezoidal region somewhat like the one implied by the flexibility constraints discussed above. This is illustrated in Figure 7. The choice of investment levels within the bounds described by these regions is then determined by a linear programming model that evaluates investment activities by means of the behavioral, cash-flow, pay-back principle. This principle captures the commonly used business and farming practice of ranking investment projects by the speed with which they will "pay for themselves". The RP models, applied to the steel and coal industries (Abe, Day, Nelson and Tabb [1978], generate the typical wave-shaped curve of capital accumulation and decumulation with its stages of accelerating adoption, declining adjustment, obsolescence, and obsoleteness.

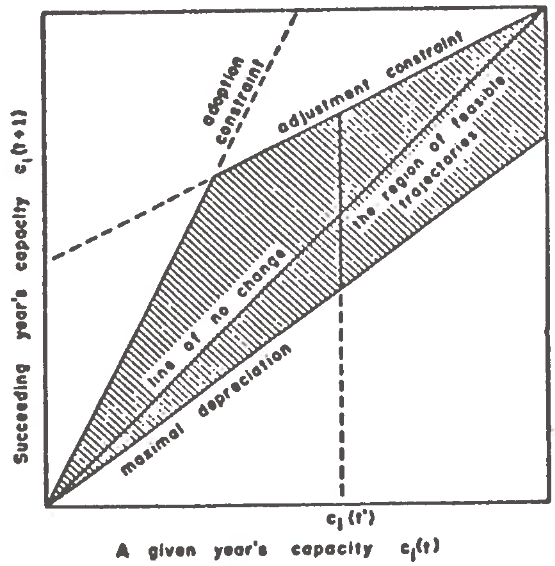


Figure 7. Phase diagram for an individual capital good. The trajectory of capacity must lie within the convex, shaded region.

Source: Day and Nelson (1973).

Sequential Attention to Goals

Early work by Cyert and March (1963) emphasized the multiple goal character of motivation and the sequential attention to multiple goals in real decision-making processes. Optimizing theory encompasses these phenomena in the form of lexicographic preferences or utility (Georgescu-Reogen, 1954; Encarnacion, 1964; Ferguson, 1965) and in more general programming models in the form of lexicographic or priority programs (Day and Robinson, 1973). The latter involve the sequential optimization of a set of ordered objective functions. Any given optimization is constrained to the set of optimizers of the higher order objective functions. This model of decision-making for a given period is made adaptive by embedding it in a feedback model that relates the objective function data (and satisficing levels) to previous experience and data about the economic environment. The result is a recursive programming model. Such a model is tested by Day and Singh (1977) in a study of agricultural development in the Punjab.

Other RP Models Based on Optimizing Tactics

Another group of RP models that are based on adaptive optimizing tactics, but which do not use the cautious suboptimizing principle include the work of Heidhues (1968), Steiger, and de Haen (See Heidhues and de Haen [1978]. The feedback in these models comes through capital accumulation and decumulation, and working capital constraints that relate current working capital and brrowing capacity to past economic performance. More or less similar models have been applied to urban housing development by Hartwick and Hartwick, to commercial banking by Walker and Castner, and to petroleum refining by Lindsay [1978].

The Adaptive Optimizing Strategy

We recall from Section 2.6 the basic structure of the adaptive optimizing strategy. The decision-maker has a model of his environment based on past observations and inferences from experience. On the basis of this model the long-run consequences of current actions can be estimated and current choice optimized with respect to them. This is called an optimizing strategy because in making plans according to it the decison-maker accounts for the total situation as he perceives it. This model of decision-making is then embedded in a model of the complete system of environmental feedback. If the decision-maker learns, his model of the environment will change as will his concept of the best strategy. This is why the model is adaptive.

A model of behavior based on such considerations consists first, of a dynamic programming, optimal control, or multi-stage linear programming component. This component represents the agent's strategic planning procedure. The second component is a set of feedback relationships that models the agent's "true" environment and how the agent changes his conception of the environment (his strategic planning model) in response to "true" environmental feedback. In order to study the effectiveness of a given strategic planning procedure for describing or prescribing behavior, each of these elements must be included. Analysis or simulation of the system as a whole then reveals its dynamic, homeostatic and "true" optimality properties.

The first point to be emphasized in discussing this approach is that the strategic planning components must be based on a radical simplification of the agent's overall problem Simon [1957, p 169]. This is because solutions of dynamic programming models can only be derived or computed for very limited types of models. Hence the strategic planner's rationality is bounded by computational capability as well as perception and the accuracy of scientific inference. For this reason the adaptive optimizing strategy shares with the adaptive optimizing tactic the fundamental structure of approximate or local optimization with feedback.

Strategy Versus Caution

Because his planning procedure must be so drastically simplified, and because so much will be learned in the course of behavior, the adaptive person may well question the usefulness of complex, long-horizon plans. He is likely instead, to incorporate strategic considerations only when he has evidence that farsighted behavior pays off. He will often limit the scope of possible action to a perceived safe-enough set.

Nonetheless, some accounting of strategic considerations, if in a simplified form, is an important aspect of human behavior. This is especially true with economic choices involving durable goods that are produced or whose services are consumed over extended periods. An example of this approach to modelling behavior was proposed by Day (1963) and applied by Müller and Day (1978) to the study of the hog cycle. The latter model consists of (1) a multi-period linear programming submodel that describes production, (2) an adaptive expectations hypothesis of price forecasting, (3) cautious optimizing as described above, and (4) an environment consisting of econometric demand equations. The horizon of the agent's plan is six production periods and behavior is simulated over a 45-year period. Müller's computations illustrate how strategic planning of the dynamic linear programming type without flexibility constraints leads to extreme and highly unrealistic oscillations in behavior after some 20 periods. With flexibility constraints the qualitative aspect of economic behavior is more accurately presented even though expectations are seldom realized. It is the latter fact that variables exogenous to the planner's model must be forecast, a pervasive one in economic reality, that confounds optimal strategic planning and calls for caution through one tactic or another.

An investigation of cautious, short-horizon behavior compared to long-horizon behavior has been completed by Sparling (1976) who found in some limited experimental simulations that cautious short-horizon (tactical) behavior performs better than long-horizon (strategic) but incautious behavior.

4. ECONOMIC HISTORY AND CHARACTERISTICS OF MODEL SOLUTIONS

4.1 The History of Economic Variables

Before turning to a consideration of the solutions of adaptive economizing on recursive programming models, we should remind ourselves of certain salient features of actual economic development processes. After all, qualitative and quantitative facts are the things we want to understand and over which we hope to exercise improved control. We very briefly look at energy development and urban evolution.

Energy Development

The current controversy and confusion over energy policy and the apparent suddenness with which abundant supplies turn to scarcity, back to temporary gluts, and then back again to scarcity has brought to the fore a need to improve our understanding of how economic systems work. Although noneconomic considerations are important, the forces affecting the energy picture are imbedded in the working of the economic system. Indeed the energy problem is interrelated with a host of other pressing economic problems like stagflation, exhaustible resource depletion and urban decay and redevelopment. Its solution hinges on our correct understanding of how the present economy works, how it can and should be controlled or modified.

The pursuit of this improved understanding is greatly complicated by the richness of patterns displayed by energy related activities as they unfold through time. Such patterns exhibit at various times growth, oscillation, or decay. Aggregate energy use, like most other indexes of economic activity, has displayed a generally increasing growth mode for millennia.

Within this broad pattern constituent variables have exhibited cycles or fluctuations of varying amplitudes and durations. Complicating the empirical picture are overlapping waves of activity, sequences of growth, decay, and demise that occur beneath the surface of aggregate growth as new technology is introduced, competes with already established technology, rises to dominance, and is replaced more or less gradually by still newer modes of production or consumpton.

The wave-like pattern is well illustrated by the components of energy supply. Originally, in food collecting and primitive agricultural societies, human muscle provided most of the energy for production and consumption. Next, animal draft power, wind and wood-fueled fire provided dominant sources of power, all directly or indirectly based on renewable solar energy sources. In the course of the Industrial Revolution, coal and water power began to take over, then petroleum emerged as a dominant source of energy. Nuclear energy has been slowly expanding until recently when the Three Mile Island accident raised doubts about its safety, which may indicate that the technology for controlling nuclear energy is not yet perfected. Now we are witnessing a switch back to prominance of coal and to renewable, solar energy sources.

The point is that economic change rarely exhibits balanced growth--except in highly aggregated variables and when important declining variables are omitted. Instead it is characterized by advances and declines, by counterpoints of growth and decay.

Urban Growth and Development

These complex patterns: overlapping waves of growth, oscillations and decay and shifting phases or epochs, manifest themselves not just in the energy sector but throughout economic structures. They are relected dramatically in urban life as the organization and development of cities respond to changing technologies of production and distribution. Homes once heated by wood shifted to coal, later switching to oil or gas. Goods once distributed entirely by animal draft, are successively transported by rail or barge, then truck. Mass transit systems spread to all major urban areas, are allowed to decay, then revitalized, redesigned and extended. Patterns of home and factory design and location evolve in response to these and other changes in technology and organization.

Stages or Phases of Growth

Orthodox or conventional economic analysis has made considerable progress in providing plausible explanations of the wave-like trajectories of economic activity. For example, economic historians and development economists have emphasized an aspect of economic change closely related to these waves of activity and having very broad significance for an understanding of economic change over long periods of time. These are periods of history usually called development stages characterized by specific types of activity and dominated by specific types of constraints. Development stages switch from time to time leading to a succession of distinctly different epochs that vary in structure and behavior. Although the various historical theories of growth in which economies were held to pass through a unique, very small number of stages in an immutable order have been refuted, the grain of truth which they recognize is the existence of periods of development, which we here call phases, that are distinctly different than others with more or less abrupt switches among them.

Recent contributions to the economic literature have begun to move away from the balanced growth models to temporary equilibrium and disequilibrium models. Sophisticated techniques are being applied to generate more realistic trajectories while retaining model specifications in the orthodox framework. But there remain certain features of reality that need increased emphasis. These include both the typical trajectories endogenous to the economic system outlined above that must be explained and the characteristics of economic structure that are responsible for generating them. Among these features is the intriguing phenomenon that disequilibrium tends to emerge rather suddenly and unexpectedly from what seems to be well-adapted behavior, as we can readily witness in the energy and urban scenes. Thus there is a need for new approaches and techniques that will enable us to address energy, urban and related problems. The models here being considered are a part of a step in that direction.

4.2 A Changing Emphasis in Economic Dynamics

During quarter century following World-War II, economic theorists turned their attention away from problems of explaining depressions and business fluctuations to the problem of characterizing growth. A flourishing literature emminating from the von Neuman, linear activity analysis model of growth and the Solow-Swan-Tinbergen neoclassical model of growth focussed attention on the existence, stability and intertemporal optimality of balanced growth trajectories. In the meantime members of the behavioral economics, system dynamics, recursive programming and evolutionary modelling schools were building mathematical models that exhibited trajectories of a far more complex character than those that were receiving so much attention in pure theory. These complex patterns, indeed, display just the characteristics of economic history that we observed above. They would seem, therefore, to be of compelling practical and theoretical interest.

The character of these trajectories may perhaps best be introduced by considering specific examples. We first take a look at a number of model generated trajectories using the recursive programming approach. We then review some dynamics of extremely simple, single equation models that share some of the essential features of more complex, adaptive economic, recursive programming or evolutionary models.

4.3 A Dynamic Model of a Prototypical Electric Utility

We first consider Economic Dynamics Electricity Model (EDEM) described in Economic Dynamics Inc. [1980], a model intended to represent behavior in a prototypical electric utility. The structure of the model is similar to the Baughman-Joscow [1979] model of electric power generation but includes economics of scale, lumpiness of investment, financial feedbacks and cautious suboptimizing responses to technological innovation along the lines described above in Section 3.

A simplified flow chart is pictured in Figure 8. The key module is the capacity expansion or planning component in which investments are determined, choice of technology is made, and construction of plants is advanced or delayed. This expansion decision is made on the basis of information about future fuel costs, construction costs, and demand passed from the forecasting module, as well as a budget constraint obtained from the financial module. The forecasting component uses simple extrapolative "rules of thumb" to predict future patterns of cost and demand. It does, however, receive information from a demand module which contains a demand

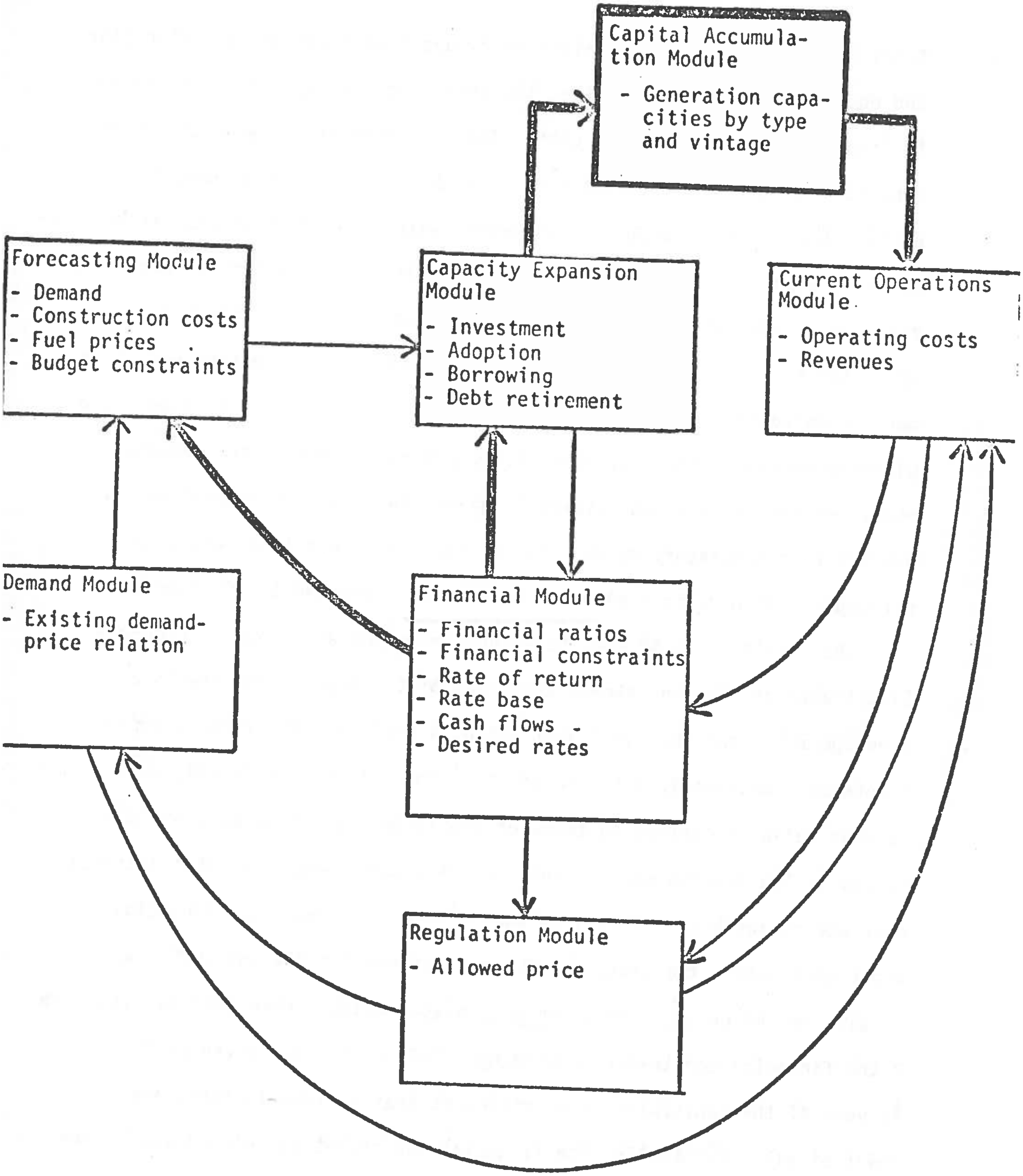
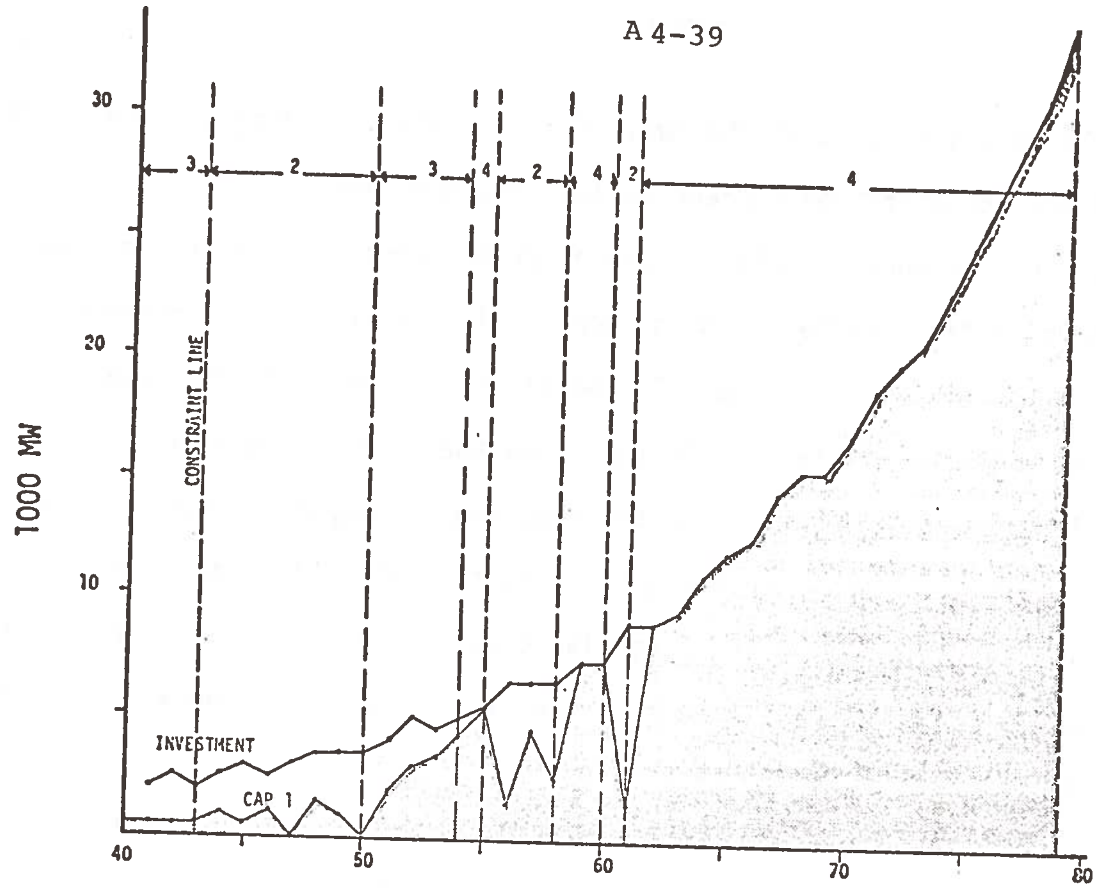


Figure 8: The General Structure of EDEM-I

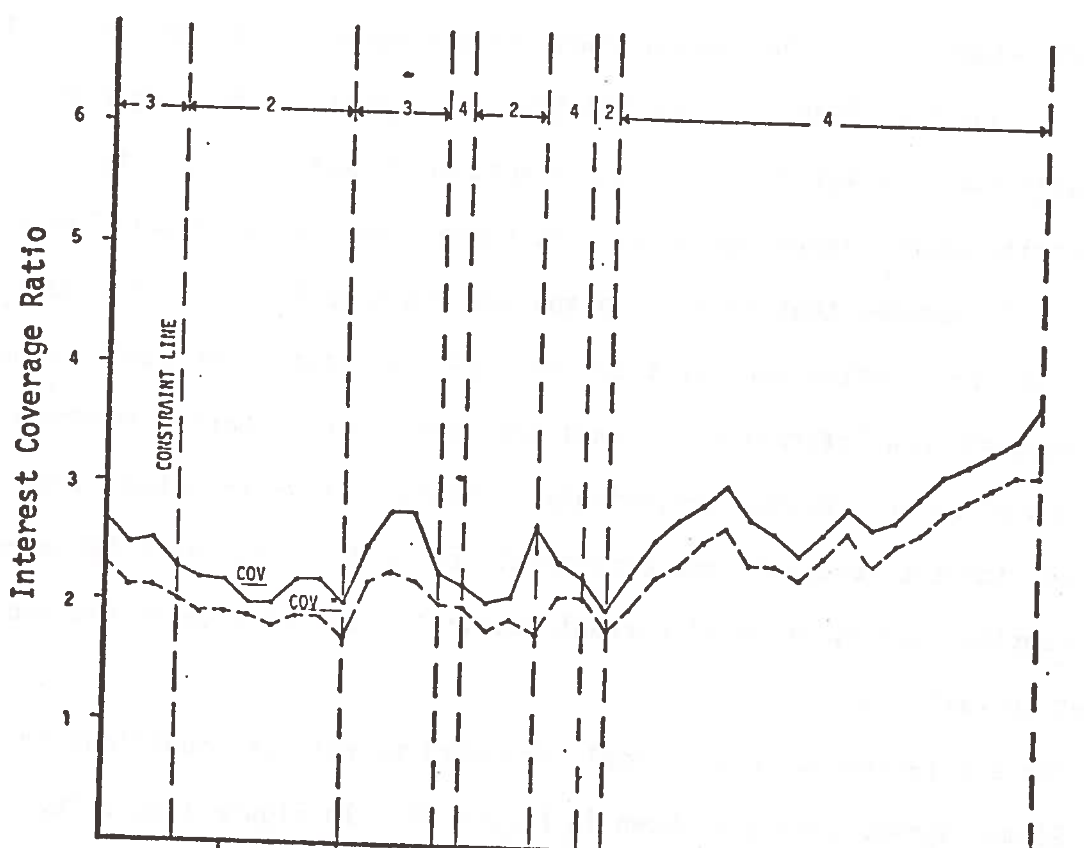
Source: Economic Dynamics, Inc. [1980]

function and time paths of various exogenous demand variables. With plant and equipment chosen and on line, the current operating module is activated to "run" the system at lowest cost. This is necessary because our prototype utility does not forecast perfectly the time paths of demand and costs. The financial module is concerned with financing the capital requirements of expansion. This is done on the basis of internal funds (retained earnings, depreciation) and external borrowing, which is subject to an upper limit. It is assumed that internal funds are used before resort is made to borrowing. The financial constraint feeds into the forecasting and planning modules. Finally, electricity prices are set in the regulatory module on the basis of an externally given "fair rate of return" and are subject to a regulatory delay. The overall structure is a recursive, strategic, decentralized planning model with environmental feedback.

The results of a 40 year base-run simulation are shown in Figure 9. Illustrated are the investment decisions of the model firm, the interest coverage ratio and the constraint which is binding. The firm, a rapid innovator, immediately hits the adoption constraint. While this constraint reflects caution in terms of the technological aspects of technology 1, the immense capital costs of this technology mean that interest coverage ratios begin to fall so that within four years the financial constraint enters the picture. The curves labelled COV and COV* respectively are the _ex post_ and _ex ante_ coverage ratios. When COV* is less than 2 the financial constraint is binding. This occurs for seven periods. In year 47 the constraint is so stringent that no type 1 plants are built at all. Eventually, the financial constraint is relaxed and a pure demand mode (4)is entered. Even as late as year 61, however, the financial constaint is a consideration. These latter phase 2 cases reflect i



6(a)



6(b)

Figure 9: Base Run (500 MW Plants)

part the lagged effects of the fuel-intensive plants coming on line which has an adverse effect on current period coverage ratios.

In another model simulation the adoption/innovation constraint was altered to reflect different management attitudes toward the introduction of new technologies. In Figure 10 the effects of being a "follower" or non-innovator are displayed. In this case the firm does not introduce technology 1 before year 55 when the exogenously supplied industry experience convinces it that the new generating technology is safe. This has the effect of alleviating the financial constraints associated with adapting the new technology but because of inflation, these are more severe and last far longer than in the base case.

4.4 A Dynamic Model of West German Agriculture

We return now to the dynamic model of the agricultural sector developed by Müller and Day [1978, Chapter 10] involving cautious, rolling plans with the forecasting and market feedback in a structure formally similar to the electricity power generation model just summarized. As we recall, in this model it is assumed that farmers' plans are drawn up for a finite, multi-period horizon. After the first period passes and the first stage plans are executed, new information becomes available through market feedback and previous plans are revised accordingly. Uncertainty is relected in more or less pessimistic forecasts and behavioral constraints providing for more or less cautious modification of current activities in response to the evolving market context.

Two simulations with the model, designed to reflect conditions in West German agriculture are shown in Figure 11. In Figure 11a, a "base

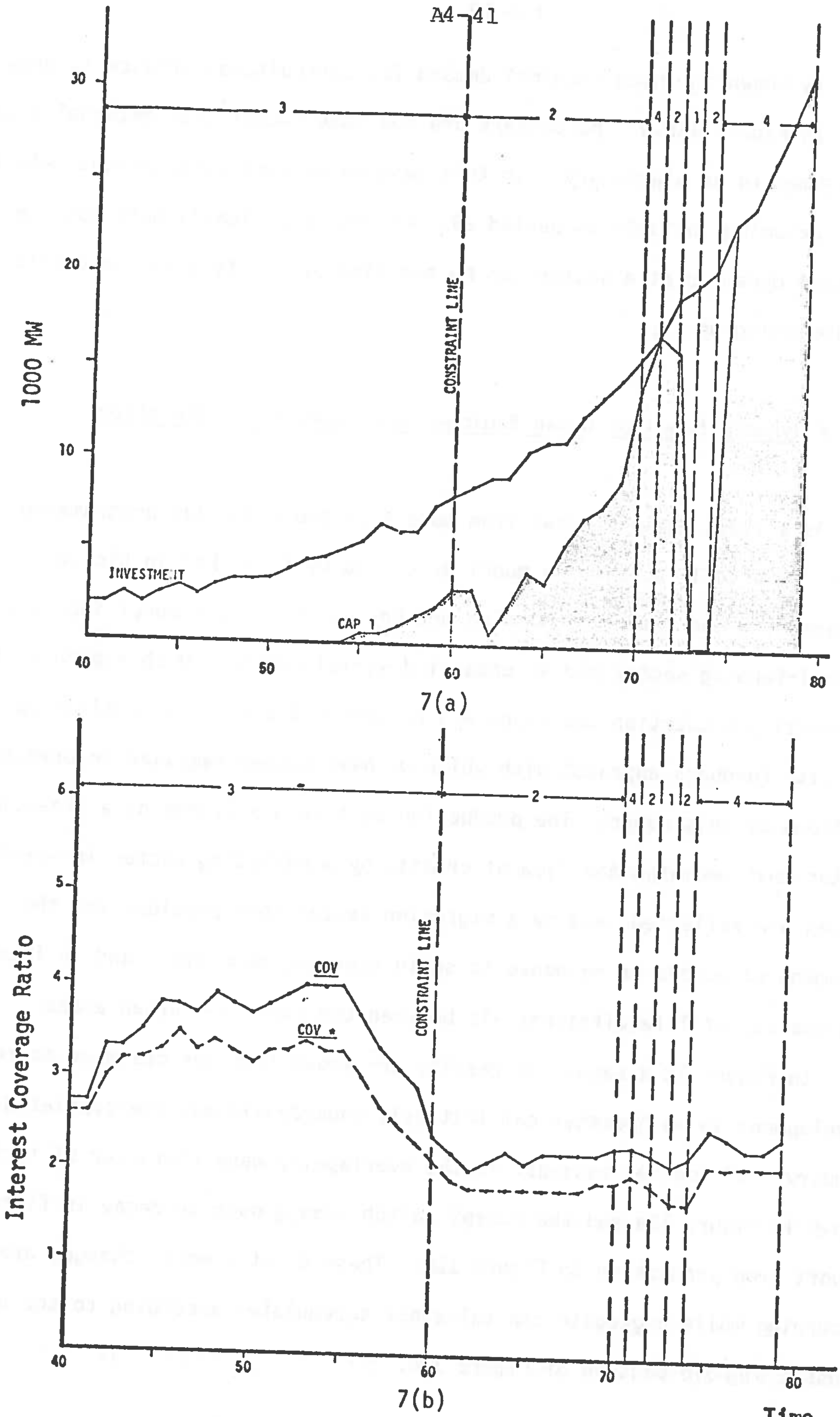


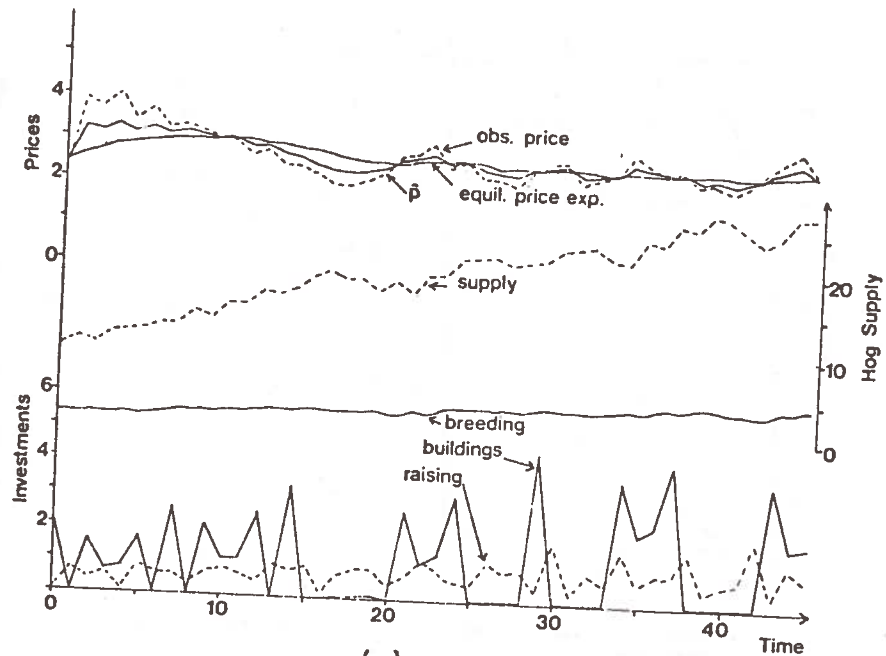
Figure 10: Slow Adopting Firm

case" is shown in which external demand for agricultural produce is growing. In Figure 11b all parameters are the same except that external demand is assumed to be stationary. In this case an extreme cycle errupts wth the model becoming inviable in period 29. We see very clearly here how the internal dynamics of a sector can be modified by events going on outside but impinging on it.

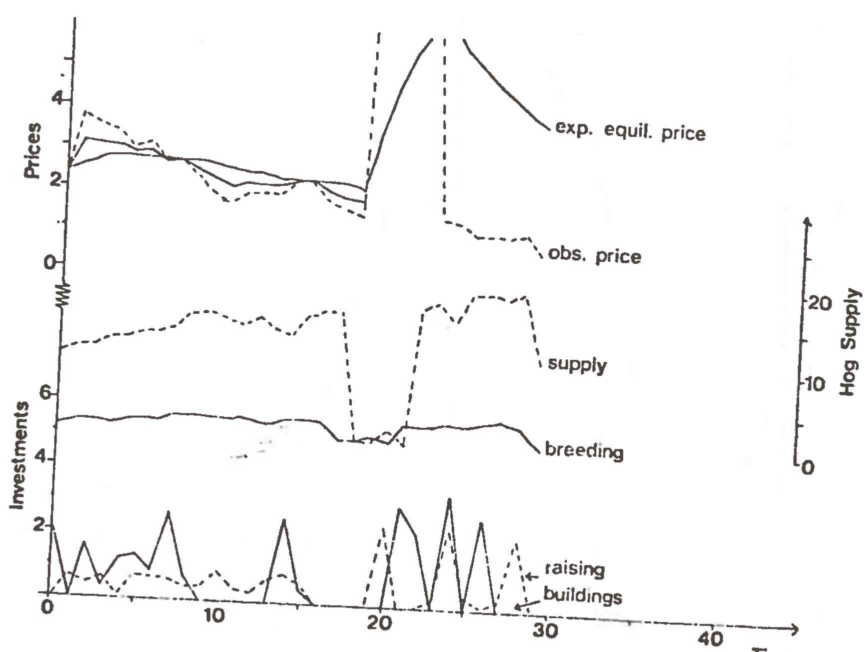
4.5 A Dynamic Model of Urban-Regional Development and Migration

As a final example drawn from models of the recursive programming genre, we briefly consider a model developed by Y.-K. Fan in his doctoral dissertation and summarized in Fan and Day [1978]. This model incorporates a rural-farming sector and an urban-industrial sector. Within each sector economizing production decisions are represented using the cautious optimizing with feedback approach with which we have become familiar in preceding sections of this paper. The production sectors are linked by a financial sector that mediates the flow of credit, by a marketing sector in which prices are reflected, and by a migration sector that provides for the movement of people in response to socio-economic conditions and to income and quality of life differentials between the rural and urban areas.

In Figure 12 a sample of results are shown that are designed to reflect development in an hypothetical initially underdeveloped, overpopulated country. Of special interest is the overlapping wave character of technology shown in Figure 12a and the "cusp" switch from growth to decay in fibre and export crop production in Figure 12b. These drastic modal changes are occurring while aggregate capital stock accumulates according to the smooth, classic Sigmoid pattern of Figure 12d.



(a) Simulation 4.



(b) Simulation 2.

Figure11: A Dynamic Agricultural Model

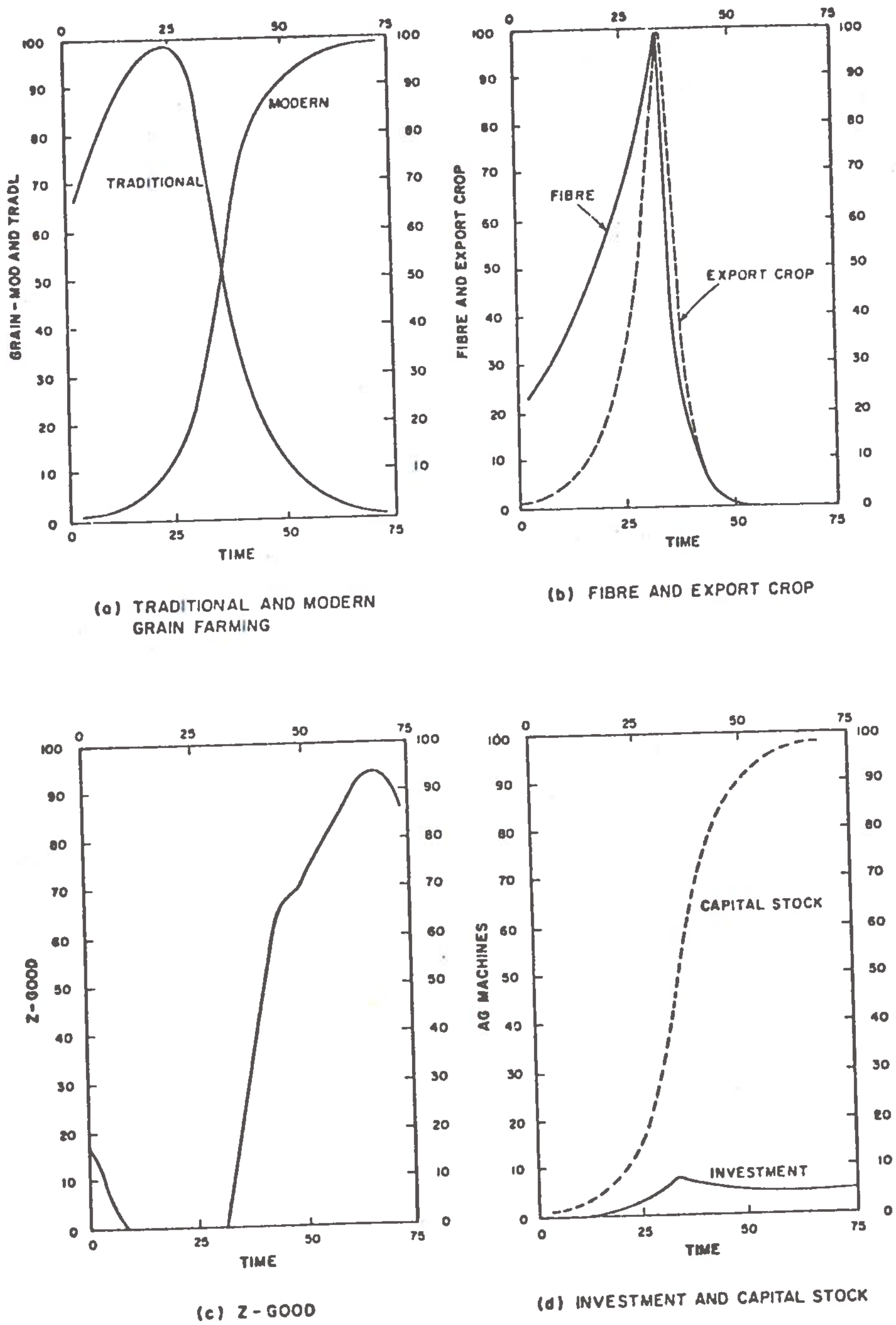


Figure 12: A Dynamics Model of Urban-Regional Development

4.6 Qualitative Features of Model Generated Histories

The examples now before us illustrate how model generated behavior mimics salient features of historical experience: the unbalanced growth, overlapping wave syndrome, irregular oscillations endogenously generated by deterministic behavior-environmental feedback interactions, the sudden emergence of extreme fluctuations, and breakdown in the model system. Evidently, the type of model under consideration has the flexibility to represent the rich variety of time paths that socio-economic variables display in reality.

5. COMPLEX TRAJECTORIES IN SIMPLE ECONOMIC MODELS

5.1 Simplified, Theoretical Analyses

Although all of the models summarized above are relatively simple examples of the adaptive economizing, and recursive programming approach, they are sufficiently complicated to make theoretical analysis quite difficult. In order to make sure that the reader does not obtain the impression that our results are aberations that arise from ad hoc computer modelling, we want to emphasize that trajectories of the kind under consideration are generic phenomona of nonlinear dynamical systems. To clarify this point we briefly summarize a purely theoretical analysis of nonlinear economic growth. The model we consider is specifically designed to be quite conventional except for the introduction of nonlinearities that lead to behavior completely overlooked in economic growth theory as developed heretofore.

5.2 The Neo-Classical Growth Theory: Evolving Modes and Chaos Day (1980)

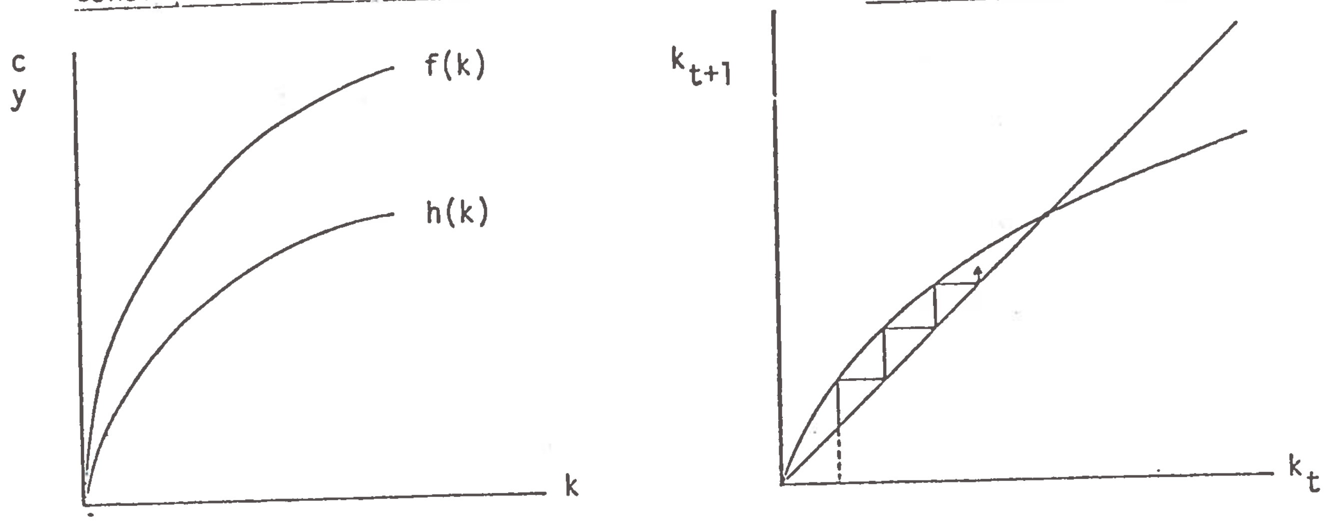
With a slight modification, the neoclassical capital growth model originated by Solow, Swan and Tinbergen can be invoked to illustrate endogenously evolving modes and complex oscillations in investment and GNP. A society is assumed to save a portion of the capital it inherits and of the income it produces. In the original Solow-Swan-Tinbergen form, the savings ratio is assumed to be constant and production is assumed to be determined by the familiar power function. In this case growth proceeds in an orderly progression, converging to the famous balanced growth path. Such a path was generally anticipated by economists in the sixties to hold indefinitely in reality.

If however, we introduce a nonlinear dependence of the savings ratio on the rate-of-return, that is, on the marginal product of capital, or, if we allow a productivity diminishing factor representing pollution to bend the production function downward, then it can be shown that virtually endless variety can appear in the model solution.

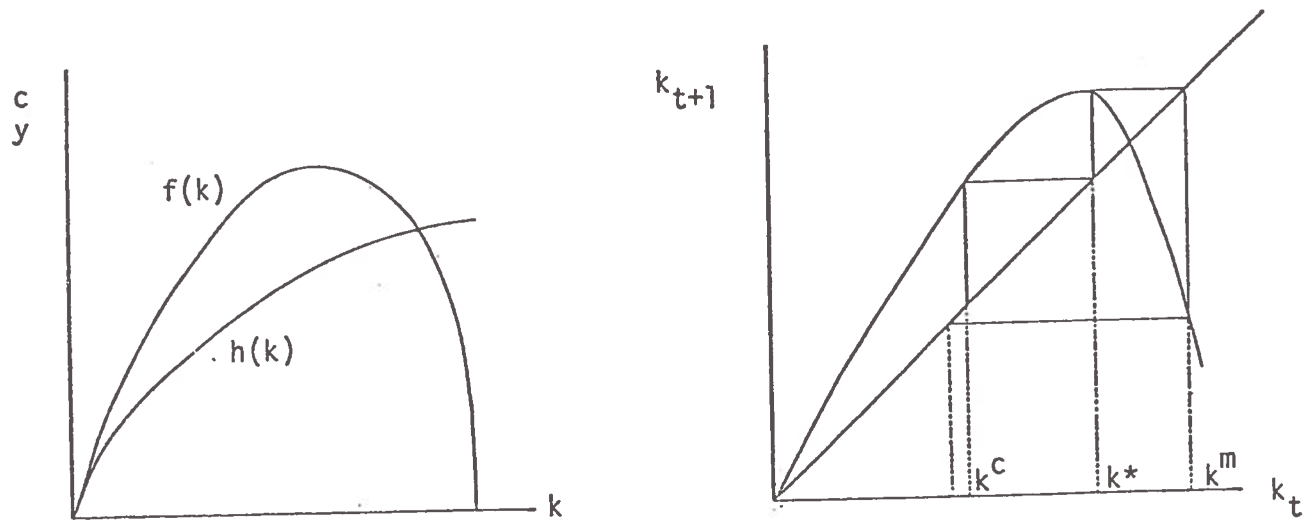
In Figure 13 three different sets of assumptions about technology and behavior are shown. In (a) we have the standard case in which the system converges to steady - state, balanced growth. In (b) the production function is bent downward by the productivity inhibiting "pollution" effect and in (c) the wealth effect is shown in which per capita consumption rises sharply as wealth increases. In both the latter cases an overshoot of the steady state occurs. Instead of converging to a steady-state, balanced-growth path a variety of complex patterns can emerge. Among them are trajectories called chaotic in the mathematical literature (Lorenz 1963, Li and Yorke 1975). Chaotic trajectories are bounded oscillations that wander away from cycles of any order so they are not periodic or quasi-periodic. In addition, any two chaotic trajectories, no matter how close they come to one another, wander apart!

The endogenously generated, complexly evolving modes of behavior possible in such a model are shown in Figure 14. First, exponential growth appears. Then the steady state is exceeded and irregular cycles appear, followed by a period of almost steady-state behavior. Out of this period of balanced growth emerges an oscillation which displays the wandering saw-tooth pattern typical of chaos (and of many economic variables.) The extreme instability of such trajectories is illustrated in Figure 15 where model solutions for a slight perturbation in initial condition (15a) and savings parameter (15b) are superimposed an the "base-run" of Figure 14.

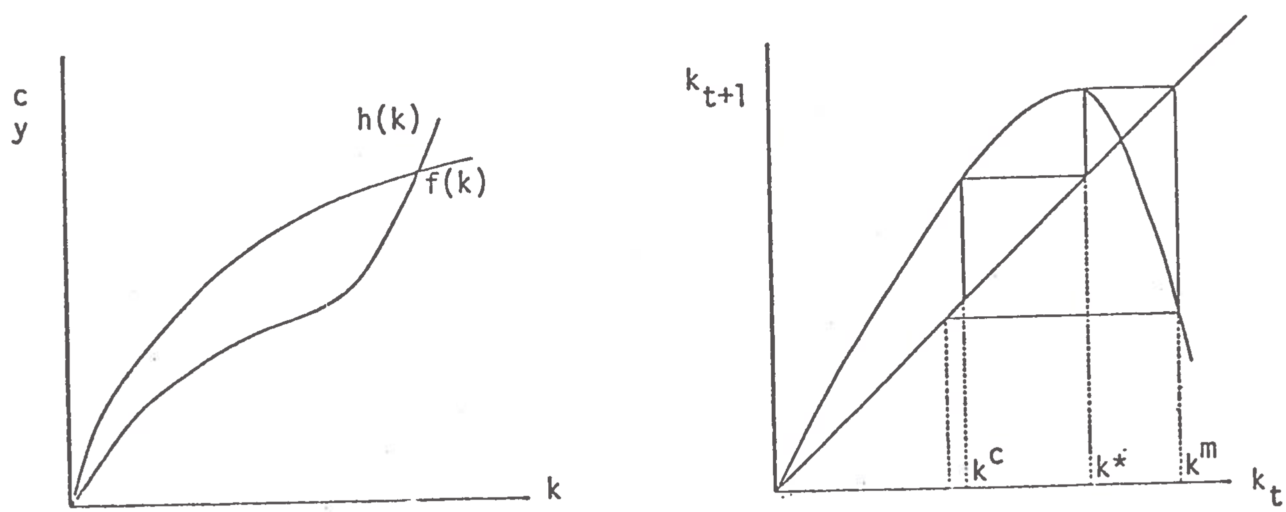
Consumption & Production Functions | Phase Diagrams for the Capital-Labor Ratio



(a) Constant savings ratio with the power-production function.

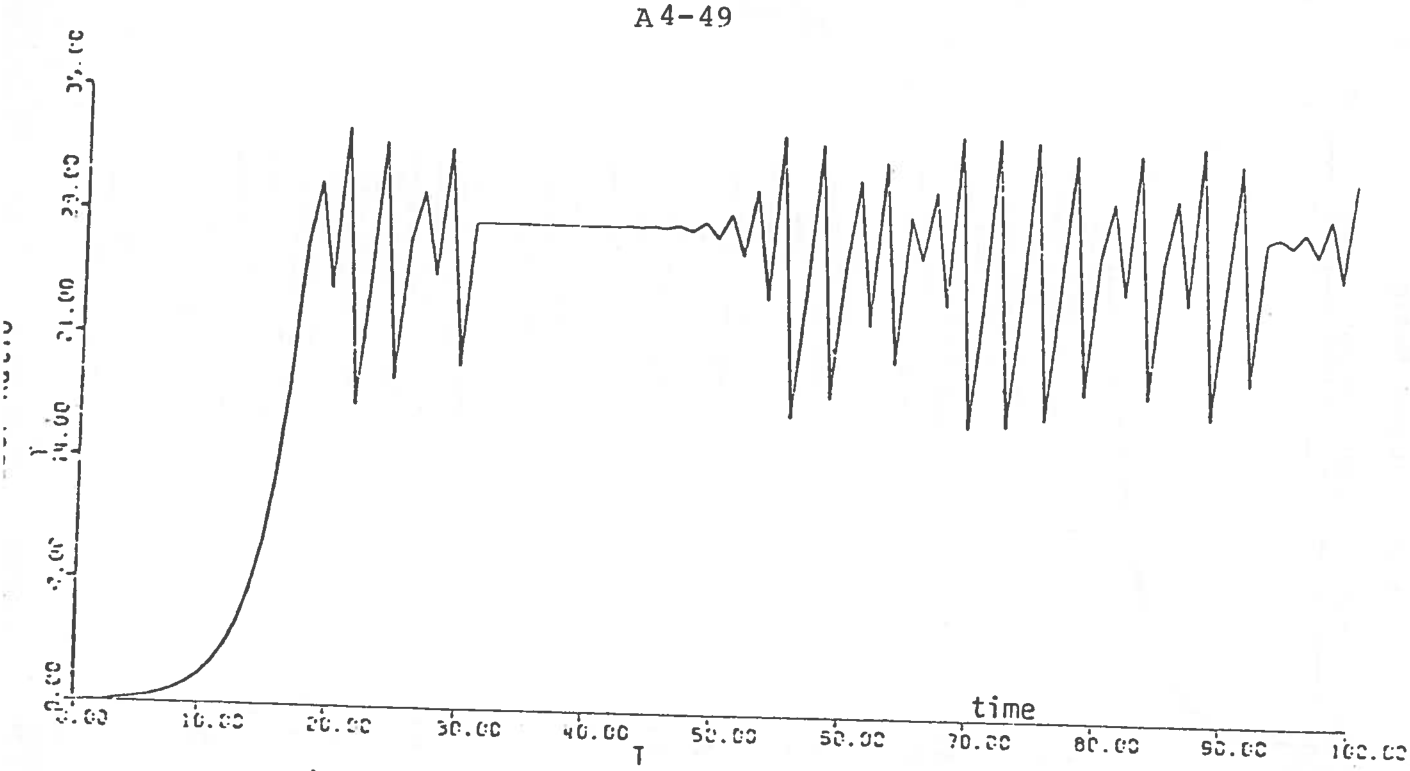


(b) The Productivity Inhibiting Effect

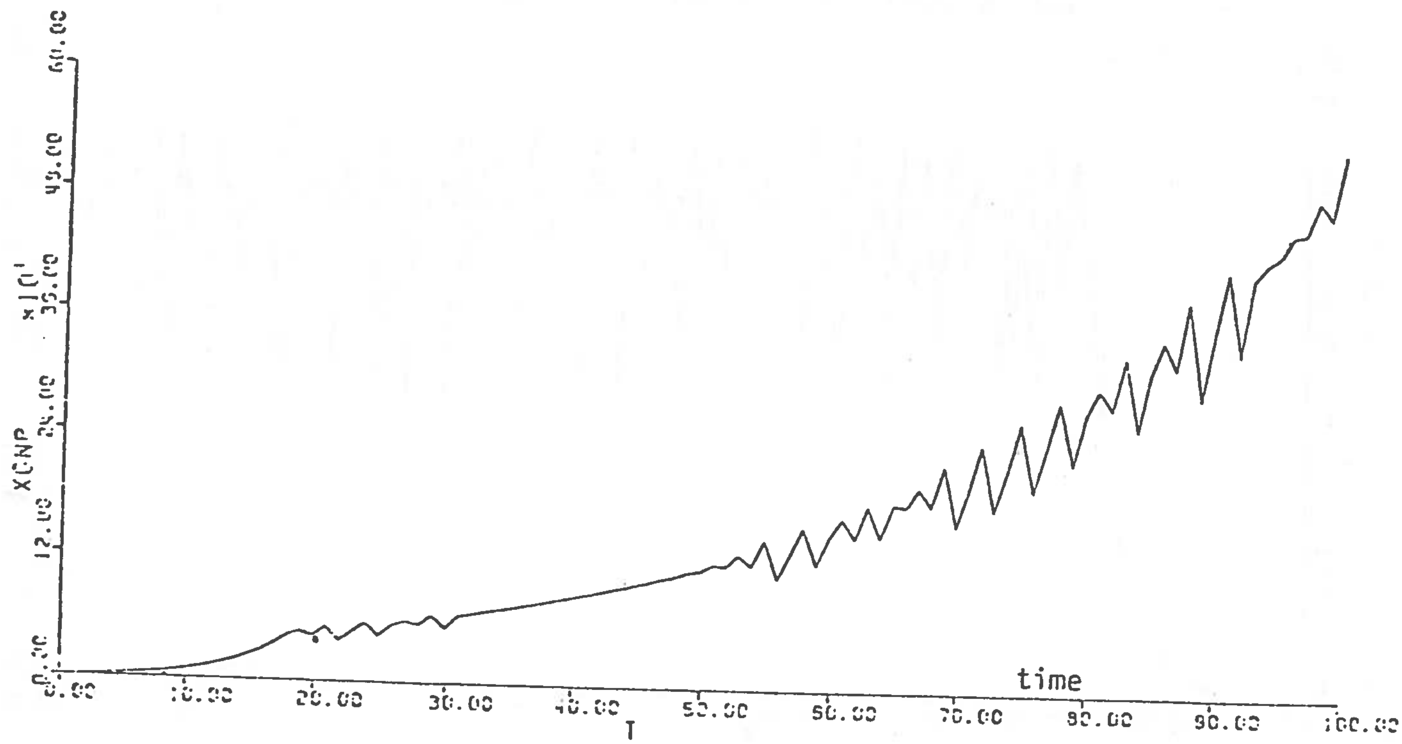


(c) The Wealth-Consumption Effect

FIGURE 13: THE WEALTH-CONSUMPTION AND PRODUCTIVITY EFFECTS AS SOURCES FOR THE CHAOS CONDITIONS

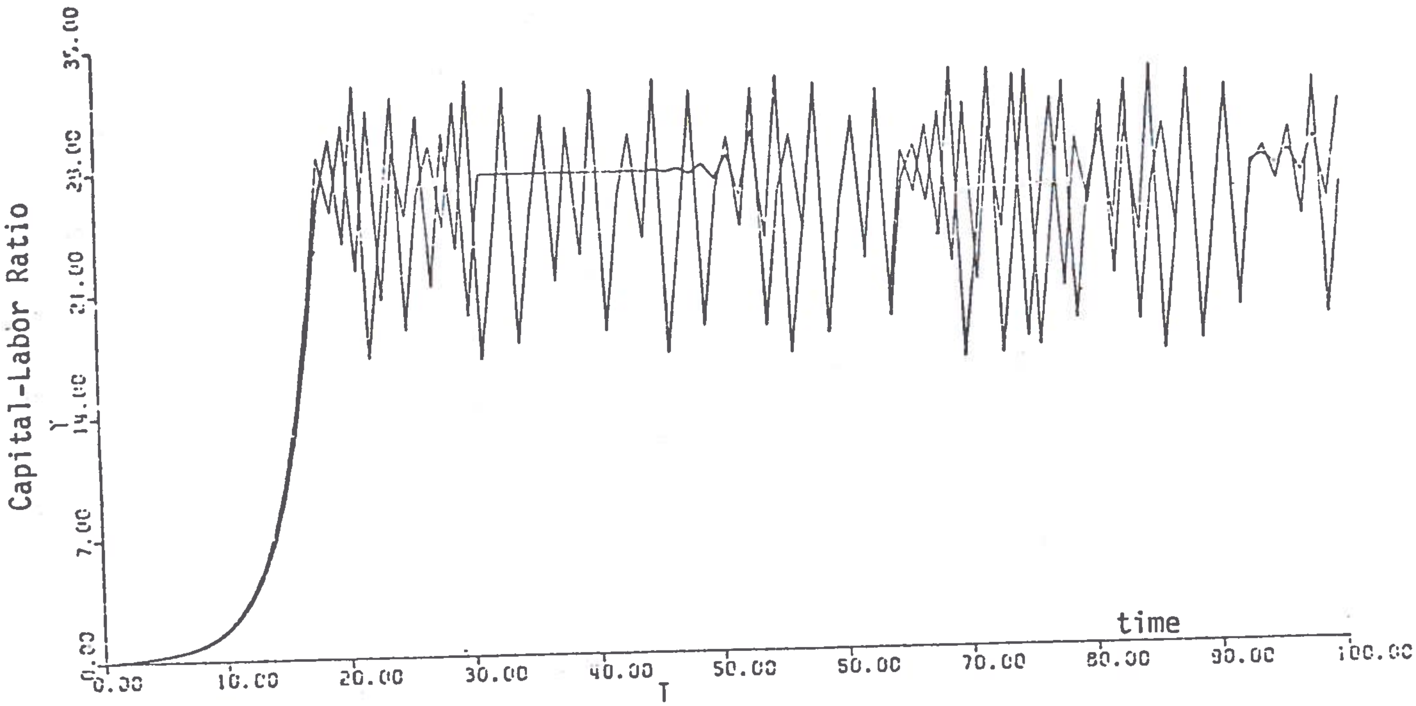


(a) The Capital Labor Ratio

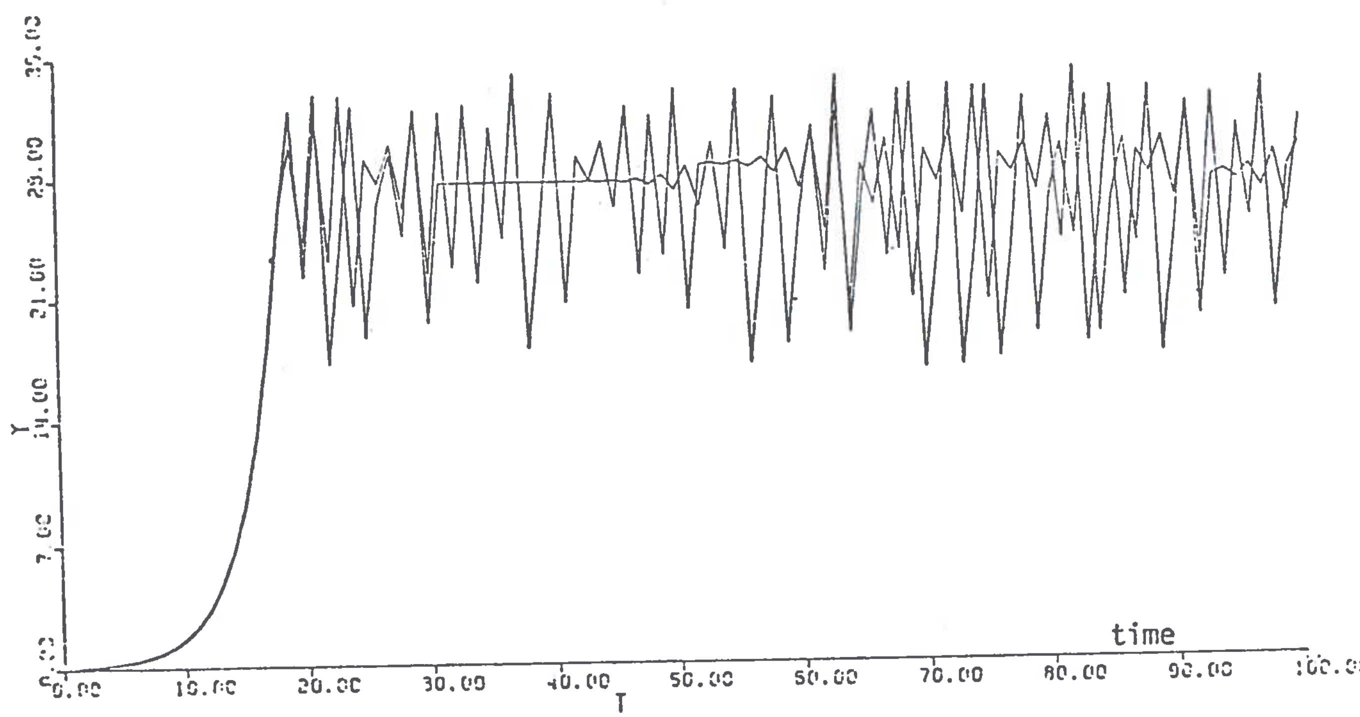


Growth and Cycles in GNP

FIGURE 14: CHAOS IN A GROWTH MODEL.
From Day, "Irregualr Growth Cycles," Working Paper #8022, MRG, University of Southern California, October 1980, p. 2.



(a) A Small Perturbation in Initial Conditions



(b) A Small Perturbation in the Savings Parameter b.

FIGURE 15: INSTABILITY OF CHAOTIC TRAJECTORIES

(Note that the trajectories wander away, wander close, and wander away from each other as time progresses.)

It should be emphasized that, as illustrated by the simulations, nonlinear models may evolve through apparently different regimes even though no structural change has occurred. This suggests that past behavior of a nonlinear system may be a poor guide for inferring even qualitative let alone quantitative patterns of change in the future.

6. UNSTABLE SYSTEMS, INTELLIGENCE AND ECONOMIC EVOLUTION

Theoretical and empirical models of the kind that have been our concern in the preceding pages seem to lead to a coherent, very general theory - or to use a currently favored expression, a new paradigm of economic development and cultural evolution. Although the complete development of this theory or paradigm is an undertaking that probably cannot be completed, to paraphrase Karl Jaspers, it remains, nevertheless, a task. In any case its outline is clear in my own mind and in this section I want to share my view of that outline.

In a nutshell: adaptive behavior implies disequilibrium; disequilibrium requires the existence of disequilibrium mechanisms; the dynamics of these mechanisms are unstable and involve overlapping waves, irregular oscillation, decline, demise and breakdown; the synthesis of new systems is the product of human intelligence whose necessary existence is established by the underlying analytical dynamics; this intelligence probably operates according to a dialectical process; successive technological and organizational innovations complexify the system, initially stabilizing it and so making it able to function; but the newly constituted system goes through its own growth, oscillation and decline with breakdown inherent from the beginning.

Let us review this sequence of thoughts in slightly more detail.

6.1 Adaptive Behavior.

Economic adaptation involves an interaction of people (decision-makers or agents) with their surrounding environment including their organizational mileaux. The behavior of agents is, in part, rational and involves explicit choice, economizing and, more generally, optimizing. But people's knowledge of environmental structures is incomplete, their store of data and memory is limited, and their powers of cognition and computation are severely circumscribed. Rational choice therefore involves problem simplification and problem solution often must involve adaptive learning of an elemental kind. Because adaptive decision makers cannot solve problems perfectly, actual behavior involves a blend of rational choice, of traditional or standard operating procedures, and servomechanistic, negative feedback adjustment mechanisms.

6.2 Disequilibrium Mechanisms

It follows that coordination among the members of a group, economic organization, or culture is imperfect. Disequilibria should therefore typify actual situations. This means unfulfilled expectations, inequations in supply and demand, and worsening situations for some while others improve. Because of disequilibrium, survival must be a key concern in adapting economic systems. The specific homeostatic or adaptive motivated feedback behavior is one type of strategy evolved to bring about homeostatis in the general sense, that is, to maintain critical variables within bounds that define survival. Learning and explicit optimizing models must have come into being to serve this same purpose. Special economic institutions: stores, order mechanisms, monetary systems, and resource transfer schemes have also come into existence to mediate economic activity in disequilibrium. Needless to say these strategies and organizations do not always succeed. For this reason one should expect to observe variation and selecton in rules, in individuals and in organizations. In short, an economy will evolve.

6.3 Unstable Trajectories.

Although equilibria, balanced growth or stationary states may be brought about within a given dynamical system, even simple examples are capable of overshoot, oscillation and more extreme forms of catastrophic change. These unstable modes of behavior are to be expected and may be the rule rather than the exception in adapting processes. Particularly when resource scarcities are involved we must expect to find either deterioration and eventual demise of resource dependent activities or overlapping waves of technology as new methods, products, and resources replace old ones in a succession of technologically based epochs.

6.4 Crises and the Intrusion of Intelligence.

Such discernable epochs, identified by characteristic economic and social activities and by characteristic resource inputs unfold typically in a progression of growth, irregular oscillation, decline and more or less rapid and final demise. In the process, crises emerge that threaten the working of the system. If people are to continue living the system must accommodate newly constituted organizatinal forms. Thus, a creative intelligence must exist whose function is the design and establishment of new rules and organizations that will avert the crises and set the system in motion again. For example, during the bank holiday in the agricultural crisis of the 1930's a new cooperative banking system was established. For another example, at present, in response to the financial crisis in electricity production, a flury of searches is under way to find new technologies, new methods of finance, modified pricing and environmental regulations and novel new methods for smoothing both demand and supply.

It seems doubtful that creative intelligence operates in the realm of ideas like the dynamic, mathematical systems that are the basis for our theory of economic change, oscillation, crisis and breakdown. The opposite possibility should not be ruled out, but at this stage this human agent of morphogenesis should probably be thought of as a distinct force whose operation may best be described as dialectical as opposed to the analytic which is used to explain its necessary existence. From the dialectical point of view analytical models are artifacts of human intelligence, intermediate products that serve as inputs in some grander dynamics of mind and culture that involves curiosity, investigation, reflection, theorizing, argument, persuasion, debate, compromise and synthesis.

6.5 Intelligence as the Effector of Cultural Variation.

The creative intelligence that lies behind cultural evolution must be as old as man. Because of its function humans alone among living things on earth transcend the blind and profligate forces of biological evolution. Genetic variation and selection is augmented by cultural adaptation and selection. Once, set loose it continues to work whether in immediate need or not. It creates a cadre of seers and inventors, then scientists and engineers, who busy themselves creating new ideas new organizational forms, new technologies for material transformation, which can be set in place when and if they are needed and prevailing conditions are propitious for institutional change.

6.6 Complexification and Inherent Potential Instability

As specialized production and exchange grow, new institutions or enterprises will be introduced to mediate the new disequilibria in supply and demand. These institutions and enterprises will buffer and ameliorate the imbalance that precipitated their adoption. At the same time, they introduce new decision-points -- often requiring new decision-makers (new agents), new information requirements,and new delays. This implies a new level of complexity and a possible increase in potential instability.

The new system will work well for a time precisely because of new technologies, new rules of behavior or new organizations. But it must eventually pass through the typical pattern of growth and oscillation. Through its growing complexity it has increased its inherent potential for chaos and crisis. It is inevitable that that potential be realized.

We must imagine that people caught in a matrix of shifting fortunes due at times to rapid, perhaps catastrophic shifts in economic opportunity and constraints, will not always stick with past organizations, but will search for new or different rules of organization and behavior, adopting some from among the inventory made available by creative intelligence. They will as a result introduce new mechanisms to govern adaptations.

6.7 The Development 1 Counterpoint.

Economic development becomes a kind of fugue blending in dialectical counterpoint the themes of novelty and growth, of demise and decay. Cultural evolution more and more becomes a frenetic race between the human faculty for creation and the dissembling forces which intellectual artifacts eventually unleash. The outcome of the race, its goal or destination - if such exists - can scarcely be guessed. To run this mysterious race it seems is mans fate: La Condítion Humaíne.

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The Dynamical Analysis of Urban Systems : An Overview of On-Going Work at Leeds.

* Beaumont, J.R., Clarke., M, Keys, P**, Williams, H.C.W.L.
and Wilson, A.G.
School of Geography, Leeds.

* Department of Geography, Univeristy of Keele, Newcastle-U-Lyme, Staffordshire, U.K.
** Department of Operational Research, University of Hull, Hull, U.K.

(1) Introduction.

In this short paper we present an overview of a programme of research dynamical systems analysis being undertaken at Leeds. No attempt is made to give a detailed analysis of this work, instead, references to appropriate publications are given wherever relevant. The work programme consists of two main strands of model development: firstly the application of dynamical systems theory to examine the evolution of urban spatial structure; and secondly the use of micro-simulation in socio-economic and public policy analysis. These are addressed in turn.

(2) Applications of dynamical systems theory : catastrophe theory and bifurcation.

Research on applications of dynamical systems theory to urban and regional systems started in Leeds in 1976. First, it was quickly recognised that such research offered exciting new insights into the workings of such systems, and so it became an important element in our work on systems theory in a broader sense; secondly, it provided a new basis for the construction of a comprehensive urban model which was one of the most important application areas of our current programme of research.

The work began with some rather speculative research on the possible applicatons of catastrophe theory following the publication of Thom's well-known book in English in 1975. Catastrophe theory is, broadly, a theory of discrete change in systems. This can be interpreted, for real systems, as being a more sudden change than can be predicted by the more usual 'comparative static' equilibrium models. The first application was to modal choice in the transport model (Wilson, 1976-B). This notion predicted a hysteresis effect which has subsequently been found empirically

(Blase, 1979). The second application considered, as a phenomenon, the relatively sudden change in retailing structure, for convenience goods, from a 'corner shop' economy to a 'supermarket' one. A model based on catastrophe theory was proposed (Poston and Wilson, 1977) which offered new insights.

What has subsequently turned out to be a more important field has developed from a study of the differential equation which, it had been argued (Wilson, 1976-C), might govern structural change in retail and similar service systems. These equations take the form

$$\dot{W}_j = \varepsilon (D_j(W_1, W_2, \ldots, W_N) - kW_j \qquad (2.1)$$

where W_j is the scale of the retail facility in j, $\dot{W}_j$, the rate of change, D_j the revenue attached to j, and ε and k are constraints. ε measures the scale of response of the system when it is not in equilibrium - the equilibrium state being given by

$$D_j = kW_j \qquad (2.2)$$

k represents the unit cost of supply. D_j is calculated from the usual spatial interaction model for retail sales and is given by

$$D_j = \sum_i \frac{e_i p_i W_j^{\alpha} e^{-\beta c_{ij}}}{\sum_k W_k^{\alpha} e^{-\beta c_{ik}}} \qquad (2.3)$$

The most striking feature of the set of equations (2.1) is that they are strongly interdependent, because each W_j depends on all the W_k's and they are non-linear because of the form of D_j in (2.3), particularly arising from the denominator which represents the effect on sales of other centres. The interdependence and non-linearities between them ensure that there are multiple solutions to 2.2; that is , there are (or more precisely, may be) multiple equilibrium states.

The study of such sytems is the subject matter of bifurcation theory. This is a more general approach then catastrophe theory since the underlying differential equations, like (2.1), do not have to be gradient systems. It is concerned with the identification of *critical* values of the parameters of the system (like α, β, k and ε - but also including all exogenous variables later, $\{e_1\}$, $\{c_{ij}\}$ and $\{W_k\}$, $k \neq j$, for zone j) at which the nature of the solutions of (2.1) change. This may refer to a change in equilibrium states and involve discrete change, as in catastrophe theory; or it may involve changes in the nature of the solutions of (2.1) when the system is not in equilibrium.

The first breakthrough in the analysis of the system represented by equations (2.1) - (2.3) came when it was realised that the right-hand sides of (2.2) and (2.3) could be represented graphically and that any state equilibrium points would be at the intersection of the two curves (Harris and Wilson, 1978). Two cases are shown in Figure 1.

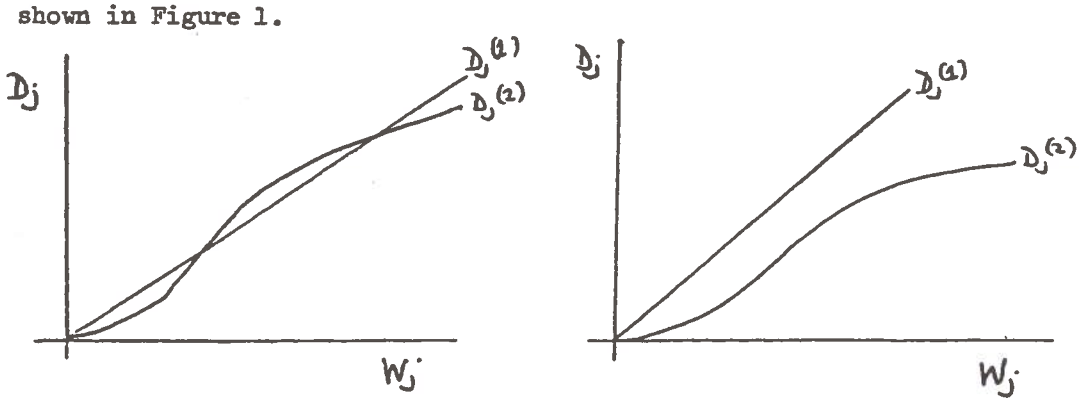

Figure 1.

[$D_j^{(1)}$ calculated from equation (2.2); $D_j^{(2)}$ from equation (2.3)]

If k is constant, it is the slope of the $D_j^{(1)}$ line. If it changes over time, there is a critical value, depicted in Figure 2. For greater values of k, there is no non-zero equilibrium in j (no development possible in the NDP state); and vice versa (the DP state).

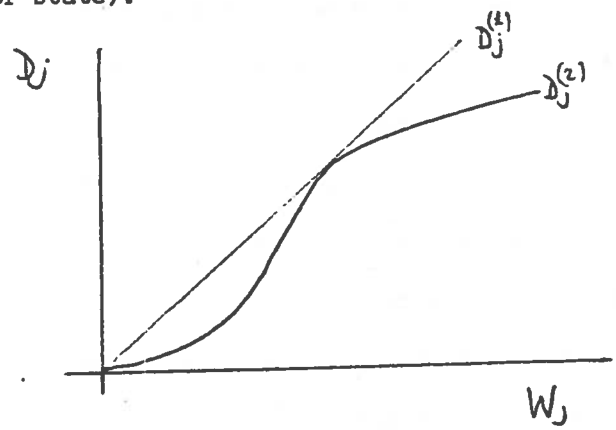

Figure 2.

This insight alone provides an important result for the analysis of urban development and the basis of a revision of central place theory (Wilson, 1978). We carried out numerical experiments which showed that the problem was particularly complicated because of the dependence of the $D_j^{(2)}$ - curve on $\{W_k\}$, $k \neq j$ (Wilson and Clarke, 1979). The problem thus identified is part of our proposed ongoing research problem in this field.

The next step was the analysis of the system in disequilibrium. It was possible to use some theorems of May (1976) derived for ecological models to show that the system could exhibit new forms of bifurcation behaviour at critical values in the response parameter ε, including transitions from steady growth to periodic solutions (Wilson, 1980). These non-equilibrium forms of evolution were also studied numerically both in the context of changing energy parameters (Beaumont, Clarke, and Wilson, 1980-A) and for urban structure more generally (Beaumont, Clarke, and Wilson, 1980-B). These experiments have been wide ranging and a monograph is now in preparation on the results (Beaumont, Clarke, and Wilson, 1980-C).

The results of this research have been presented at a number of conferences and there seems to be a general feeling that it could represent the beginnings at least of a more explicit dynamical theory of urban systems. A more complete account is offered in Wilson (1981). It is on this basis that we would intend to take it further in our current research by seeking to add realism by modelling real systems and by extending the number of subsystems in the model. The addition of new interdependent subsystems can always generate new bifurcation phenomena.

(3) Micro-simulation in socio-economic and public policy analysis.

(3.1) Introduction: the micro-simulation approach.

In this section we discuss the methodolgy, application and potential use of micro-simulation for the analysis of socio-economic and public policy issues. Although the general micro-approach dates back to the study of household dynamics by Orcutt and his colleagues in the United States (Orcutt, *et al.*, 1961) the number of applications - particularly those involving a spatial dimension is very small and spread sparsely across several fields, as reviewed by Clarke, Keys and Williams (1980-A). An important contribution both to methodology and application was made by Wilson and Pownall (1976) and one of the main emphases on the current project has been to combine the focus on *interdependence* stressed by those authors with the dynamical considerations of Orcutt, *et al.* (1961, 1976).

The approach was originally motivated by a requirement to consider

in detail the characteristics of attributes of individuals (or households, firms, etc.) as a basis for the analysis and explanation of particular socio-economic phenomena. An explicit recognition of the high degree of heterogeneity in a population when each member is characterised by the values of several attributes, and the requirement to confront the aggregation problem directly prompted a consideration of an efficient representation of the state of the system. It became apparent that the computational listing and manipulation-list processing of samples of micro-units (individuals, households, etc.) multiply classified by the various demographic, social, economic and activity attributes relevant to a particular context was highly preferable to the manipulation of a large and typically very sparse occupation number matrix, whose elements are the number of individuals cross-classified by the various attributes of interest. The simulation methodology thus involves listing vectors of M attributes $\underline{x}_i = \{x_i^1, \ldots, x_i^\mu, \ldots, x_i^M\}$ for each memeber i of an N membered population or sample P. The storage of NM elements associated with these N vectors $(\underline{x}_1, \ldots, \underline{x}_i, \ldots, \underline{x}_N)$ will typically be very much smaller than the number of elements in the occupation number matrix. This quantity is given by $\prod_{\mu=1}^{M} \alpha^\mu$ where α^μ is the number of classes associated with the μ^{th} attribute.
Recent work (Wilson and Pownall, 1976; Clarke, Keys and Williams, 1980) has emphasised the importance of micro-level interdependency or more formally the structure of correlation in the joint distribution of attributes $\rho(\underline{x})$ over the population, to be a crucial determinant of the efficiency and advantage of the 'list-processing' method.

The considerable advantage of working with the micro-representation in which the characteristics of individual decision units are listed and manipulated according to the processes which induce transitions between system states, is in its capacity to retain all information associated with the variability and interdependency between attributes of those units which might otherwise become lost if aggregate quantities are formed directly from individual data, as is generally the case in urban modelling. Consider for example a typical micro-level description of an m_j membered household H_j which we shall represent as a list of characteristics of all constituent members $I_i \varepsilon H_j$, $i=1,\ldots, m_j$, together with relevant summary measures of joint characteistics pertaining to the household as a whole:

$$H_j \{\ldots\{I_i^j (\underline{d}_i, \underline{m}_i; \underline{e}_i; \underline{A}_i) \}\ldots \{\underline{d}^j, \underline{m}^j, \underline{e}^j, \underline{A}^j\} \} \qquad (3.1)$$

In this description are included the following vectors

$\underline{d}$ = the demographic characteristics (age, sex, race, etc.)

$\underline{m}$ = sources and measures of income.

$\underline{e}$ = sources and measures of expenditure

$\underline{A}$ = activity-travel characteristics (including characteristics relating to employment, housing, shopping, recreational, activities, etc.).

In the specification of urban models the information collected in this set of attributes is often partitioned in aggregation and classification procedures. In particular, loss of information is usually associated with simplifiying assumptions relating to

(i) the interdependence between the attributes of individuals

(ii) the interdependence between the characteristics of individuals within a household.

While independence assumptions may be justified in certain circumstances, for many applications, some of which we shall consider, it is inappropriate to ignore the complexity of the joint distribution of attributes both within and between households.

In the dynamic simulation models to be described the effects of various demographic, economic and social processes responsible for transitions between states are represented in a set of differential equations which are solved using Monte Carlo procedures by forward iterative through time (Clarke, Keys, Williams, 1980-A). Conceptually this is quite straightforward and involves charting the likely paths through time of each individual/household in a sample which is set up as an initial point in time, the base year. Changes of state are recorded according to the relative values of random numbers (between 0 and 1 sampled for each individual and the probabilities of the relevant event (birth, death, marriage, job change, move, etc.) for those individuals. The characteristics of the sample are continually updated according to the results of this 'processing' which ensures that over the sample as a whole the number of events occurring will be in accord with the transition probabilities injected into the model.

Computationally, this procedure involves the formation and manipulation of cross-referenced lists of individuals and households. In complex models incorporating several processes it is necessary to ensure that the solution of the dynamical equations is achieved with the minimum amount of list searching consistent with the logic of dynamical behaviour. Any relevant information relating to individuals or households cross-classified by various attribute sets may be extracted from the 'updated' sample at any time period, as required.

The information required for solving these equations and in particular the initial samples, may be attained in purpose designed surveys or derived from various primary or secondary data sources. In the applications we are developing to explore the use and potential of the approach we have not had the resources nor was it within our terms of reference to invest in primary data collection. We have therefore resorted to many different sources of information in order to set up samples appropriate to the different study contexts, and have adopted statistical synthesising techniques to generate a joint probability distribution $\rho(\underline{x})$ from which an initial population is sampled. This distribution is constructed in such a way as to be consistent with any available information on the conditional and marginal distributions of its attributes. The procedure is discussed at length by Wilson and Pownall (1976), McFadden, *et al.* (1977), Macgill(1978) and Clarke, *et al.* (1980-A).

(3.2) Contexts of analyses.

The state of a system at any future time is a function of both the interplay between demographic, economic, and social processes and also importantly of the initial state of the system - the distribution of characteristics over the relevant population - which can of course show a very strong geographical variation between and within regions or cities. In the series of applications to be discribed it has been our intention to draw out both these aspects in dynamic models.

A number of general characteristics of the approach may be illustrated with reference to Figure 3.1 in which some aspects of the interaction between labour and housing systems are examined (Clarke, *et al*, 1979). The actions of individuals in the labour market and of families as consumers (and investors) in the housing system 'pivot' on the household, which is described by a joint array of the attributes of its members. These attributes may be updated according to the equations governing individual actions. A micro-model of household dynamics is developed involving the

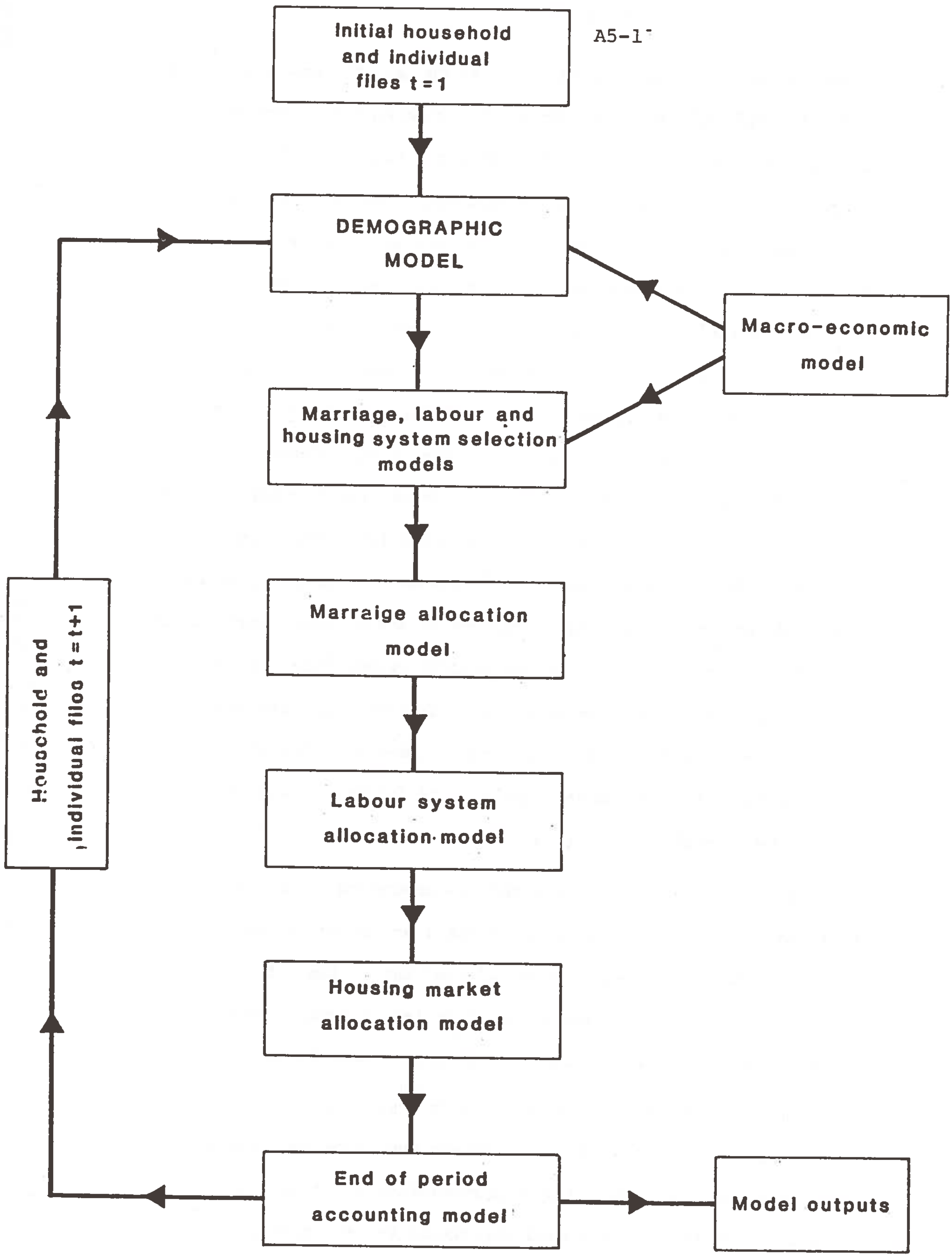

Fig. .1 Structure of micro-simulation model processes accompanying household formation, growth, and dissolution and the supply of labour and demand for housing are formed by aggregating over the actions of individuals and households respectively. These supply and demand equations pertaining to the labour and housing systems respectively are interfaced with econometric/time series models for the demand and supply of housing, through allocation models which we shall discuss in a little more detail below. In this way the economic and demographic driving forces of the system may be allowed to interact and the effects of projected changes in say the demand for labour allowed to percolate through the household attributes to the demand for housing (or,more generally, services). At a more fundamental level the actions of households, characterised by many relevant demographic, social and economic attributes, may be related to the economic environment which their actions are partly and jointly responsible for. The solution preocedure for the equations characterising this model is illustrated in Figure 2. A few more comments on the allocation models which allow demand and supply to be interfaced within a stock-flow representation are in order.

In the analysis of housing and labour systems it is necessary to relate the propensities of individuals or households to change state - to enter, leave, or move 'within' the system - to the external conditions of housing supply or labour demand respectively. In both systems it is necessary to recognise that the exchange of a 'durable' entity such as a house or a job can set up a chain of moves, and that this chaining process should be represented at an appropriate level of system resolution in model applications. Although this feature of mutual dependency between moves, and the existence of 'exchange movers' is an important characteristic of housing and labour systems it is generally ignored in the formation of dynamic models.

We have developed an appropriate framework for including such aspects of behaviour, and have incorporated in a number of dynamical models a clear distinction between new entrants to the system on the one hand, and those internal transitions on the other, which contribute to both the 'demand' and 'supply' sides as noted in Figure 3.1. The models require a consistent documentation of all possible transitions between system states and these are expressible as coupled equations governing feasible stock-flow conditions in the housing and labour systems. Such equations may be given both network and matrix representations (Williams, *et al.*, 1980; Williams and Wilson, 1980). The definition of appropriate characteristics of individuals, households, jobs and dwellings must of course be geared to the specific context under study.

The stock-flow equations must be augmented by particular assumptions in order to derive forecasting models. Various models have been formed based on both prior information on transitions and on economic determinants in decision contexts. In the former category we have constructed fractional flow models analogous to vacancy chain renewal processes in stochastic representations (Byler and Gayle, 1978) and entropy maximising/minimum information adding models derived by mathematical programming methods. The latter are particualrly suitable when the allocation process is subject to a set of constraints such as is involved in the housing system when the total supply of available credit is less than that demanded. In the formation of economic models the choice theoretic basis for the decision to move to a dwelling with particular characteristics is integrated with the conditions imposed by supply-demand (dis-) equilibrium. Closely paralleling the applied work on micro-simulation modelling we are thus currently investigating the theoretical relationship between allocation mechanisms, mobility, and dynamical adjustments in demand and supply in stratified housing and labour systems.

In the micro-simulation models to be described the total number of transitions between states is determined form the interaction of demand and supply, and the micro-level consequences are sought through sampling form the resultant flows. For example, quantities such as $X(\underline{\beta}\rightarrow\underline{\beta}'\ \underline{\alpha})$ - the number of households of type $\underline{\alpha}$ making transitions between dwellings of type $\underline{\beta}$ and $\underline{\beta}'$ are computed in the model and if this is less than the total demand for such transitions, the 'successful' movers are determined by a random sampling procedure.

We now turn to describe individual applications in more detail. As a general comment, with respect to all applications, we would remark that lack of information has prevented the formulation of econometric micro-models estimated with observations pertaining to *individuals* in order to determine transitions of those individuals between states. We have thus based all the applications on category analyses in which prior probabilities, stratified in geenral by demographic, social and economic variables, are derived from secondary data sources. These are expressed and stored in 'look up tables' in the computational process.

We would stress that we regard the applications as not only offering quantitative insight into the particular problem contexts, but also as exploratory in identifying the power and usefulness of the approach. It is our intention to examine the sensitivity of model outputs with respect to variation of model parameters where we believe these may be subject to considerable uncertainty.

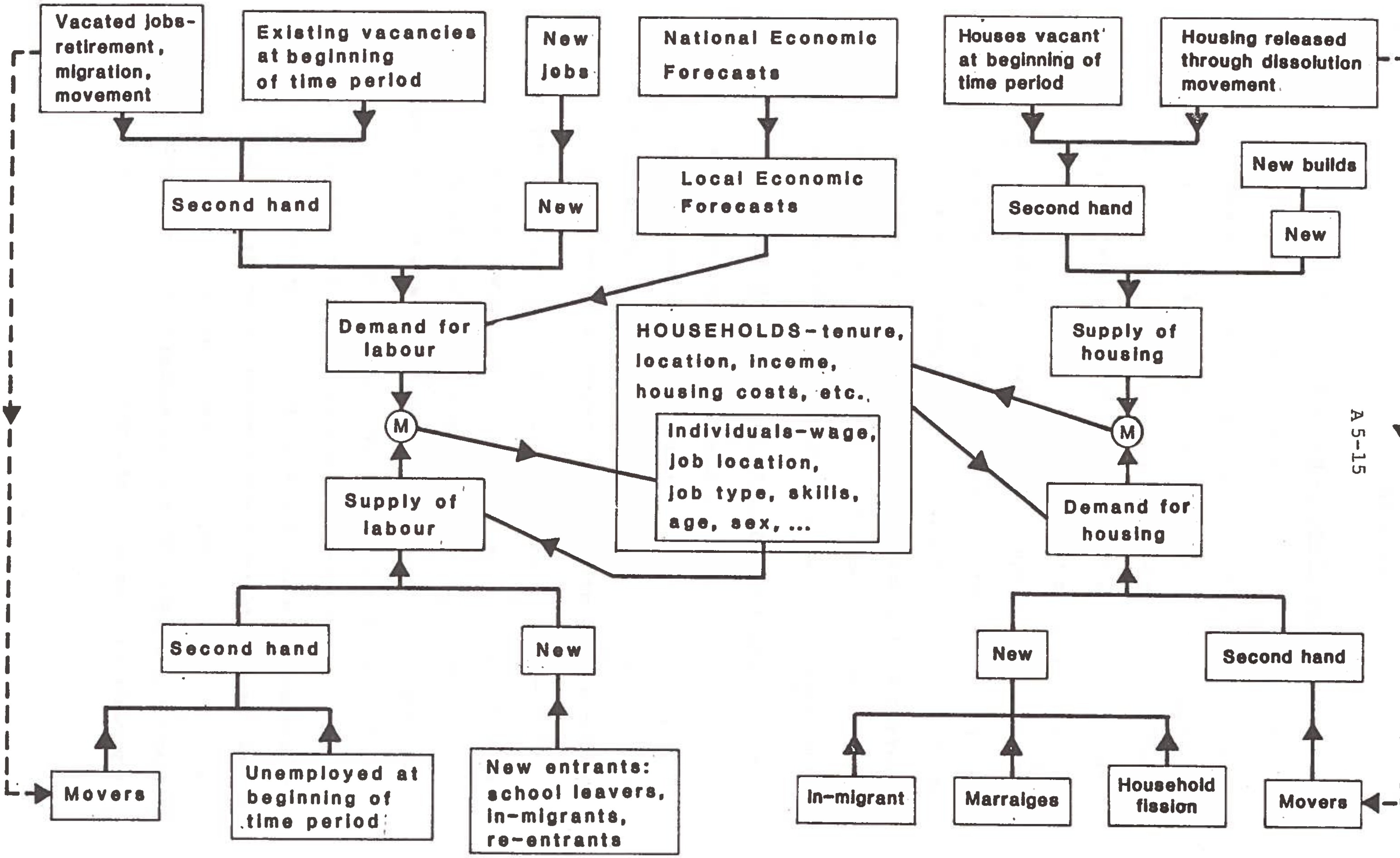
Vacated jobs-retirement, migration, movement
Existing vacancies at beginning of time period
New jobs
National Economic Forecasts
Houses vacant at beginning of time period
Housing released through dissolution movement
Second hand
New
Local Economic Forecasts
Second hand
New builds
New
Demand for labour
HOUSEHOLDS-tenure, location, income, housing costs, etc.
Individuals-wage, job location, job type, skills, age, sex, ...
Supply of housing
M
M
Supply of labour
Demand for housing
Second hand
New
New
Second hand
Movers
Unemployed at beginning of time period
New entrants: school leavers, in-migrants, re-entrants
In-migrant
Marraiges
Household fission
Movers

Fig .2

(3.3) Application of micro-simulation.

In the development of micro-simulation methods we have adopted a building block approach in which certain elements of the demographic, labour market and housing system models have been constructed. Our intention is not only to apply individual segments in contexts for which we believe the approach is appropriate, but also to progress twoards an integrated model system of the type depicted in Figure 1. The construction of models pertaining to: household dynamics; income derivation, the employment system and the demand for services; the housing system; and the interaction between the labour market and housing system are therefore discussed in turn. Another example of the application of micro-simulation in an energy context is discussed in detail in Beaumont and Keys (1980).

(3.3.1) Demographic processes and household dynamics.

Demographic change is a significant component of dynamical behaviour in the labour and housing systems, and has very important implications at the household level in relation to income generation and service consumption which we consider further below.

In traditional modelling approaches forecasts of future population and distribution of households defined with respect to various characteristics are achieved through standard cohort survival and headship rate methods respectively. Because we have been concerned with the *implications* of demographic change at the household level it was considered appropriate to study the individual dynamics of household formation, change and dissolution at that level, as a basis for generating micro-level information for the other model segments This involves, as discussed above and in detail in Clarke *et.al.* (1979, 1980-A,B) the synthesis of an initial sample of a population for the system of interest (urban area or region) and the sequential examination using Monte Carlo methods of individual households and their members for participation in various demographic events (birth, death, marriage, divorce, leaving home, and so on).

In terms of household projections alone this method may be seen as compatible with the convention approach (suitably disaggregated) and indeed uses a considerable amount of the same data.

(3.3.2) Income derivation, employment models and service provision.

Household income is derived from various sources. For the majority of households income is primarily earned by certain of its members or is derived by benefits received from government. For a smaller proportion of households, this is supplememted, to a greater or lesser degree, by unearned income/investments (Family Expenditure Survey).

The way in which different households receive and spend money is dependent upon their activity in the labour market, their position in the housing market, and other factors such as the age and number of individuals in the household. These factors also affect income from various sources: benefits, wages, and non-monetary income via services. By considering the system as a set of micro-level units - households and individuals - the decisions and processes underlying the flows of money may be explicitly incorporated into the model. Further, when these are present the impact of different policies upon the income distribution may be examined.

It can be appreciated form this discussion that many processes are involved in a complete model of income derivation. These spread over the whole socio-economic system and include effects peculiar to the demographic, labour market, housing market and services subsystems. These do not act independently to determine the money flows but interact in different ways, particularly through the household budget. Decisions made in the labour market, concerning say a change of job of an individual, will often affect the expenditure on housing, energy, transportation, etc., due to a changed income of the household of which he is a member. There is, therefore, a variety of interactions present in the system which require consideration. Those which are of sufficient importance, on their own accord or because they cause other effects, should be included in a model. A model built on a micro-level representation has the potential to incorporate the richness and wealth of interactions found in the real world. The ability of such a model to include all interactions is limited by data availability, but the micro-simulation approach at least allows all possible interactions, in theory, to be included.

The state, both at a national and local level, provides a wide range of services, such as education, health care, social services, and benefit packages that are consumed by a large and heterogeneous client group. The field of service provision has given rise to a number of policy related issues that fall into several categories. Amongst these are: determining existing and forecasting the future need for services; the allocation of finite resources between sectors and individuals (determining priorities); monitoring the efficiency, effectiveness and equity of service provision; and questions pertaining to ways of financing the cost of this provision. Current policies also demand that the effects of cuts in levels of provision can be assessed. With local authorities often being the largest single employer in an area, the role which the authority plays in the local economy is also an important topic. Some of these aspects are considered in detail in Clarke and Prentice (1980) and Clarke and Keys(1980). For example, in a micro-simulation based analysis of the consequences of local authority redundancies, it was found that a consideration of the full range of variability between households and the interdependencies between their members, allowed, *at the household level*, the influence of multiple worker effects, female participation in the labour market and benefit qualifications to be fully explored.

A further consideration of changing demand for and supply of labour and resultant mismatches are discussed within a micro-framework by Keys (1980). We are currently investigating further aspects of service provision in an urban area, and the effects of policies, such as early retirement and retraining, directed at reducing the level of unemployment.

(3.3.3) Housing models.

In the development of housing models through the 1960's and 1970's there has existed a clear divide between aggregate econometric models estimated with time series data and typically applied at a national level, and those studies of stratified housing markets applied at the metropolitan/urban level and estimated at the cross section. The former have been used to analyse and explore the dynamics of demand, supply, prices, and mortgage institution behaviour as a function of macro-economic and demographic variables while the latter have tended to concentrate on the problems of allocation and the general equilibrium (or disequilibrium) between demand and supply in stratified systems. In spite of the large number of theoretical and empirical investigations in the housing system, there do not exist at either the regional or national levels models which embrace the full dimensions of variability in expenditure, and incorporate an adequate recognition of the nature of housing as an asset, and the effects of control and metering on allocation by the institutions of tenure and finance.

We believe it was necessary (and arguably pressing) to consider in an exploratory model the effects of: asset accumulation; the large reserve purchasing power of exchange buyers; differential subsidisation; and sensitivity of housing expenditure to the movement of macro-economic variables and taxation policies. More specifically, there is a need to quantify flows of money in local housing systems and to explicitly recognise the variability in expenditure between households:

(i) over space (both intra and inter-regional)

(ii) who are 'first time' and 'exchange' purchasers

(iii) between and within tenures

(iv) with different socio-economic and demographic characteristics.

as highlighted in the comments on equity and subsidy in the recent Housing Policy review (D.O.E., 1977). This was the principal motivation of the micro-simulation study - to develop a framework within which available information on demographic (life cycle) and economic aspects of housing demand could be related to conditions of supply.

In the housing system there exist dramatic differences in both the composition of stock and the price of distribution at which dwellings become available. We are currently developing comparative regional models based on Yorkshire and Humberisde, Greater London, and the rest of the South East in order to draw out some of the salient features of housing dynamics and in particular to allow a focus on typical housing 'histories'. To construct such a model it is necessary to set up an initial sample of households with associated demographic, economic, housing finance (eg. mortgages) and dwelling characteristics, and to develop differnetial equations to represent the transition processes accompanying the interaction of demand for and supply of dwellings. This involves integrating a number of data sources in order to solve the dynamical equations in a forecasting context. A key aspect of the dynamical behaviour relates to assumptions about household trading behaviour represented in the model as prior probability distributions of moving between dwellings characterised by attribute vectors $\underline{\beta}$ and $\underline{\beta}'$ (which include price/rent). This and other information relating to the housing financial characteristics of households is currently being derived from the technical volumes accompanying the Housing Policy Review (D.o.E., 1977); regional statistics of housing transaction provided by the Nationwide Building Society and other published sources).

We are convinced that the micro-simulation framework is highly appropriate for studying the questions on household dynamics and housing expenditure variability raised above. Due to the quality of available data it is our intention to investigate these issues in a forecasting context with a strong emphasis placed on performing sensitivity analyses of model outputs with respect to key economic and demographic parameters.

While the above model is designed to explore the general characteristics of housing dynamics at a regional level we considered it of interest to examine in more detail the interaction of demographic and economic processes acting within the policy framework of local authority housing systems. It is well known that local authorities are highly discriminating in their various allocation schemes (see, for example, Murie, *et.al.*, 1976), and in order to examine these various procedures and more generally the detailed dynamics of public sector housing systems it appeared that micro-simulation was an appropriate methodology. Although some analytic work has been performed on such systems employing

Monte Carlo methods (L.G.O.R.U.. 1975; Jessop, 1970) it appeared that no systematic study had been undertaken to relate allocation and transfer policies to demand and supply conditions. In a further study we have adopted two objectives:

(i) to explore the potential of micro-simulation for the development of forecasting and policy testing models; and as a basis for monitoring changes within local public sector housing systems;

(ii) to investigate the relationship between mobility of household groups to both occupancy, allocation and transfer policies, on the other hand, and conditions in the private sectors on the other.

It is not difficult to develop a dynamical framework within which the transitions of individual tenants and members of the waiting lists can be consistently documented. This is set out in Keys and Williams (1980) and is essentially a special case of the general stock-flow accounting relations referred to in section 3.2.

Using information provided by Leeds Housing Department we are currently developing a dynamic forecasting model framework within which these various issues are being addressed. Although a full survey would be required to construct a comprehensive micro-simulation model for examining the complete range of individual transitions and relate these to economic, demographic and social processes, it again appears that the general approach shows considerable promise.

(3.3.4) <u>An integrated model system .</u>

It is our intention to integrate a number of the features of the above model applications in a 'comprehensive' model of the general form shown in figure 1. For given exogenous movements of macro-economic variables such as average wages, prices, interest rates, etc., and taxation policy, we will explore the interdependency between the labour and housing systems within local contexts, and in particular, we intend to establish how the interaction of demographic, social and economic processes influences the income and housing consumption characteristics of finely classified household groups.

(4) Conclusion.

While the two main sections of research described above may appear rather different in their nature and in their scope both are essentially aimed at solving a set of non-linear dynamical equations. An interesting question is examining if the type of behaviour that is exhibited by the models described in section 2 is to be found in the micro-simulation models described in section 3. Indeed an integration of these two strands of work is not only an important research task, it could lead to a new and very interesting set of models.

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EVOLUTIONARY PATTERNS OF METROPOLITAN POPULATIONS[1,2]

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Dimitrios S. Dendrinos[3]

Henry Mullally[4]

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[2]Part of this study was done under contract with the U.S. Department of Transportation by D.S. Dendrinos

[3]Associate Professor, Graduate Program in Urban Planning, University of Kansas, Lawrence, Kansas 66045

[4]Assistant Professor, Department of Economics, University of Missouri, St. Louis, Missouri 63121

Summary:

The bulk of the work in this report centers around data collected for 90 selected U.S. Standard Metropolitan Statistical Areas (SMSAs) over a 37-year period (1940-1977). It documents a number of interesting events which have not previously been analyzed in the literature on urban economic systems. In addition, an attempt is made to put them into their proper theoretical perspective.

A large number of questions are raised by these events, only a few of which are addressed here, albeit the basic ones. It is hoped that this paper will be a precursor of more analytic work which will probe further into the inner mechanisms of urban dynamics.

Despite the fact that the data discussed here relate to only one variable, that of the normalized population size (NPS) for selected SMSAs, a wealth of information can nonetheless be extracted. In the theoretical part of this paper the significance of the variable is discussed as it relates to per capita urban income, its companion behavioral variable in urban systems analysis. The interplay between changes in population size and changes in income underlies the dynamics of the model.

At the center of the discussion is the topic of structural stability; the resiliency of various SMSAs equilibrium configurations to (external or internal) perturbations, and the highly non-linear nature of the relationships between variables. In their effects on the NPS of cities these produce a host of interesting phenomena, including morphogenetic events.

Although the policy-related aspects of the proposed theory are not fully developed here, some significant insights are gained. For example, the widespread effects of a number of external events that shocked the national economy (including technological innovations), as well as the impact of certain large-scale government interventions in the urban system can be discerned. Most significantly, it is clearly demonstrated that, with a few exceptions, the greater part of the U.S. urban system is structurally stable.

Finally, the empirical evidence and the theory devised to explain it seem to suggest a new problematique, linking urban evolution to biological concepts of evolution, mathematical ecology, bifurcation theory, and catastrophe theory. The ecological aspects of urban evolution manifest themselves as SMSAs compete for fixed inputs (labor, capital, natural resources) either nationally or regionally, as well as competing for market areas for their basic (export) commodities. This line of research appears to be a very fruitful one along which to extend the present analysis.

A. The historical NPS profiles of 90 selected SMSAs.

Recording historical profiles of U.S. metropolitan areas' population to the total U.S. population ratios[1] (so that background, nationally prevailing, effects are eliminated) over the past 37 years, one comes across an extraordinary variety of performance.[2] However, the generic dynamic patterns that emerge out of the search are small in number and not unique to any particular SMSA. They repeat themselves with frequencies that are in accordance with what would be expected from a theoretical standpoint, and above all, these patterns are well recognized ones in the dynamics of other systems previously studied in the natural, biological, and social sciences.

The generic historical profiles, exhibited by the NPS studied, are:

- damped oscillatory movements (sink spiraling NPS moving towards a fixed equilibrium), of varying frequency and amplitude
- steady state phases, where the NPS fluctuates around a constant value over the entire 37-year study period
- relatively sharp (discontinuous) rises/falls in NPS caused by perturbations of SMSAs
- structurally stable SMSAs which, subject to perturbation(s), retained their equilibrium state and only slightly deviated to neighboring paths assymptotically guiding them to the original equilibrium
- structurally unstable SMSAs which, when perturbed, switched to a different state, thus experiencing a discontinuous motion of their equilibrium point

Oscillatory behavior

The various types of observed oscillatory motion and their relative frequencies are shown in Table 1. Two significant findings emerge: (a) there are no SMSAs exhibiting source spiraling behavior; and (b) there seems that there are no SMSAs undergoing convergence towards a limit cycle.

TABLE 1

Dynamic Patterns of Metropolitan Normalized Population Histories: a Classification Based on 90 Selected U.S. SMSAs in the Period 1940-77

Type of History			Number of Occurrences
A. Oscillatory Behavior			64
1. Sink spiral		23	
a. with steady state	6		
b. towards steady state	17		
2. Source spiral		-	
3. Orbital		1	
4. Limit cycles		-	
5. Long-term oscillatory[*]		14	
6. Medium-term oscillatory[*]		26	
B. Steady State[§]			3
C. Perturbations			21
1. Structurally stable		15	
a. switch of long-term spirals	10		
b. switch of medium-term spirals[$]	5		
2. Change of state		6	
a. naked discontinuity	1		
b. one mode plus discontinuity[#]	5		
c. Hopf Bifurcation	-		
D. Unclassified[**]			2

[*] These cases have not indicated yet whether they belong to any of the categories 1-4, since the oscillatory period is greater than the study period. For their various subcategories and their incidence, see Table 2.

[§] It includes Syracuse, NY, which may be undergoing a phase transition from steady state to oscillatory behavior.

[$] It includes one SMSA (Clarksville, TN) which switched to a different mode.

[#] It includes four SMSAs (Anderson, IN, Buffalo, NY, Chicago, IL, St. Louis, MO) which are switching from a steady state to an unidentified as of 1977 mode. It also includes Bismarck, ND, which was shifted from a (high frequency) sink spiral movement to an unidentified state as of 1977.

[**] They include Clarksville-Hopkinsville, TN-KY and Boise City, ID, that exhibit peculiar patterns that need further study to classify.

TABLE 2

The Various Long- and Medium-Term Oscillations and Their Number of Occurrences in the Sample of 90 U.S. SMSAs: 1940-77

Type		Shape(s)	Occurrence
A.5	long-term		14
	a. linear		5
	i → $\dot{x} > 0, \ddot{x} = 0$		3
	ii → $\dot{x} < 0, \ddot{x} = 0$		2
	b. concave		2
	i → $\dot{x} > 0, \ddot{x} > 0$		–
	ii → $\dot{x} < 0, \ddot{x} < 0$		2
	c. convex		7
	i → $\dot{x} > 0, \ddot{x} < 0$		7
	ii → $\dot{x} < 0, \ddot{x} > 0$		–
A.6	medium-term		25
	a. convex		–
	b. concave		5
	c. with inflexion point		20
	i →		1
	ii →		–
	iii →		16
	iv →		4