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3. URBAN MODELLING

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# *Urban Modelling*

## *Algorithms, Calibrations, Predictions*

MICHAEL BATTY

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# *Preface*

During the last decade, urban modelling has generated a momentum in Britain which has been unparalleled anywhere else in the world. In one sense, it is perhaps surprising that so 'North American' a phenomenon as the building of mathematical models of cities and regions should have caught the interest of researchers in Britain; in hindsight, this is all the more remarkable given the rather uncertain prospect for the first generation of urban models constructed in the early 1960s in North America, which preceded and promoted the British experience. Yet conditions in Britain have especially favoured urban modelling in recent years. Both the theory and practice of modelling have been stimulated by the development of an explicit 'Systems Approach' to urban research and land-use planning, and the presence of a highly developed institutional planning system has been of enormous significance in providing a natural focus for research efforts in this field. The importance of the planning system in fostering such research cannot be stressed too much, for the continuing demand by planners for better tools to explore urban problems has helped to increase the relevance of urban modelling research; and it has meant that urban models have been largely built as aids to conditional prediction, rather than solely as aids to a greater understanding of urban phenomena.

This book is a direct outcome of my contact with this movement since 1967. It reflects my particular interests in urban modelling and it attempts to synthesise some of my research writings over this period. Although I have organised the book around what I believe is a consistent framework which developed along with my research, I leave it to the reader to make his own interpretations of the material presented here. Clearly this book is not intended to be a comprehensive treatment of urban models, and thus it is no substitute for a review of the field. But I have tried to emphasise the process of modelling rather than the models *per se* and in this sense the treatment is of more general import. However, my personal biases, which are reflected in the book, date back to earlier interests.

I was much influenced by my undergraduate schooling in the Department of Town and Country Planning in the University of Manchester, and

I was fortunate in being taught by a strong and impressive but diverse group of people led by Roy Kantorowich. Although my interests were originally and continue to be in the three-dimensional attributes of cities, I was frustrated by the lack of explicit method in planning, and thus I became interested in the so-called systems approach which was being advocated in the department by George Chadwick and Brian McLoughlin. In particular, I owe George Chadwick a great debt, for it was he who persuaded me into research rather than professional practice. My initial research into design method evolved into an interest in the system being designed and I was supported and guided during these early days by George Chadwick, whose perspective on this field has helped me formulate a realistic research strategy.

Although a little of the work reported in this book was carried out in Manchester, most of it was made possible by an appointment in the Urban Systems Research Unit at Reading University. In 1968, Peter Hall obtained a substantial grant from the Centre for Environmental Studies in London, and then set up the Unit at Reading to undertake urban modelling research. An optimistic and ambitious programme was initiated and much of the work which is reported here stems from my personal involvement in this programme. From my experience with the Unit, I learnt the conventional wisdom that theory is barren without practice, and a great enthusiasm for modelling was sobered by the realisation that in Georgescue-Roegen's phrase 'there is a limit to what we can do with numbers, as there is a limit to what we can do without them'.

Many people have helped me in writing this book and it goes without saying that I wish to thank all of them. But some have played a very special role. From my Manchester days, I have mentioned the influence of George Chadwick and Brian McLoughlin but my friend and colleague Duncan Thomas, who subsequently took an alternative path to landscape architecture, had a great feeling for this area and he taught me a great deal. Dave Foot deserves a special mention, for not only did he teach me my rudimentary but essential knowledge of computer programming but he continues to guide me in the arts of the possible in urban modelling. At Reading, Erlet Cater, Roger Sammons, Eric Cripps and Jane Read have all helped me to clarify my ideas, and the influence of my M.Sc. students over the years has been considerable; indeed, Chapter 9 is the outgrowth of a project originally started by the 1971–2 M.Sc. students in Urban and Regional Planning at the University of Reading. Stewart Mackie of the Local Government Operational Research Unit originally collaborated on Chapter 8, and Ian Masser of the University of Liverpool on Chapter 10. I am especially indebted to these authors for letting me include work which they were instrumental in implementing. I realise that I have also been a perpetual nuisance to the staff of the Computer Centre at Reading. Urban modelling is a young field and enthusiasm often outstrips common sense especially in the area of computation. Thus I am greatly indebted to Tony Hewitt and his staff for the generous amount of computer time and programming advice they have given. All of these things would not have been possible at Reading without the support of Peter Hall, whose boundless energy and enthusiasm for the field has been a great source of inspiration.

I must also mention several people who have helped me on technical questions: Dick Baxter, Andrew Broadbent, Martyn Cordey-Hayes, Marcial Echenique, Geoff Hyman and Alan Wilson. All of these people have taken time out from their own researches to advise me on different points and I am grateful to them. Lionel March has helped me considerably over publication and I must thank Sheila Dance who drew the diagrams, Ann Watts for much of the early typing and Jennifer Preston for typing the manuscript. My wife Sue has helped me on all aspects of the book and only she knows the frustration of putting up with an untidy academic whose home is littered with papers. I dedicate this book to her.

Kitchener-Waterloo, Ontario MICHAEL BATTY
*October 1974*

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It is said that science will dehumanise people and turn them into numbers. That is false, tragically false...

Science is a very human form of knowledge. We are always at the brink of the known, we always feel forward for what is to be hoped. Every judgement in science stands on the edge of error, and is personal. Science is a tribute to what we know although we are fallible.

Dr Jacob Bronowski in
*The Ascent of Man*, London,
1973

# *Introduction*

Thomas Kuhn (1962), in his stimulating book *The Structure of Scientific Revolutions*, advances and demonstrates the theory that the history of science is not characterised by a gradual accretion of knowledge, as is assumed by the community at large, but is dominated at any one time by a set of fundamental ideas or a paradigm which can only be changed by scientific revolution. Most scientists spend their lives working within the recognised limits of the paradigm and only when anomalies become too significant to disregard will scientists endeavour to search for a new paradigm. This view of science is appealing and is readily endorsed by a study of major revolutions in thought such as those due to Newton and to Einstein. Moreover, there appear to exist a hierarchy of paradigms from the most general to the most specific. Kuhn's ideas can also be traced in the social sciences although such paradigms are more difficult to identify and somewhat more ill-defined than the paradigms of science.

Because the paradigms of social science are so elusive and so pervasive, scientific revolution is less easy to recognise in these fields. Yet it appears that during the last two decades, the study of man in general and the social sciences in particular have been affected by a profound transformation in approach and method akin to a scientific revolution. Although it is too soon to take a long view, the last two decades have seen the emergence of more rigorous argument in social science characterised by some semblance of experimental design and a much greater realisation of the nuances and biases of the subject matter. There is little doubt that the development of large-scale computational facilities has made these new approaches both possible and necessary. Despite the present-day view that technology presents more of a hindrance than a help to resolving the dilemma of man, it is worth remembering that many of the newer and perhaps more exciting developments in science and social science are inextricably linked to the rise of the modern computer. Nowhere is this more evident than in those fields dealing with the phenomena of man in social as well as biological and physical terms – in the fields where psychology, linguistics, computer science and engineering merge in the quest to develop 'artificial intelligence'. Immense strides have recently been made in these fields which are totally dependent on the computer, and the optimism and conviction of their scientists suggests that man is firmly set on the road to establishing what Simon (1969) has called '*The Sciences of the Artificial*'.

Urban modelling, the subject of this book, is an integral part of this revolution in thought in which the boundaries between traditional disciplines are blurring in response to the need for interdisciplinary co-operation. In short, the field of urban modelling is concerned with designing, building and operating mathematical models of urban phenomena, typically cities and regions. There are many reasons for the development of such models: their role in helping scientists to understand urban phenomena through analysis and experiment represents a traditional goal of science, yet urban modelling is equally important in helping planners, politicians and the community to predict, prescribe and invent the urban future. In education too, in its narrowest and widest senses, urban modelling can help by demonstrating the limitations of theory and the potential of simulation.

This quest is truly interdisciplinary, drawing directly and by analogy from all the sciences, and making use of mathematics, that best-developed language of science. But there are inevitable dangers in the development of such a field and two distinct dangers can be immediately recognised. First, in an era when the body of 'new' knowledge is as great or greater than the body of 'existing' knowledge, there are severe difficulties in evaluating the relevance of new theories, techniques or methodologies. There is a further dilemma in that those who know the least about the subject matter are often expected to ponder and evaluate its relevance to education, and that those who know the most about any line of research are often the least willing to speculate on its importance. These comments are not only applicable to urban modelling but to all areas of knowledge where the traditional boundaries are changing in response to new lines of inquiry. Yet perhaps the second danger is more serious. In any field where new modes of thought are not built up from knowledge already acquired in that field, it is likely that the new ideas become the prerogative of very few; this is evident in the development of urban modelling where the use of mathematical technique favours those who have acquired skills not in the social but in the physical sciences. This danger cannot be overestimated and it is well to keep in mind the old adage 'In the country of the blind, the one-eyed man is king.' Thus the approach in this book is tentative and is pursued with the view that it will take many years to evaluate the true relevance of urban modelling: hopefully this work might contribute a little to this longer term endeavour.

## A new analytical tradition

Prior to these new developments in social science hinted at above, the traditional form of theory-building and testing revolved around classical analysis. For example, in economics, one of the first areas where theory was formulated in mathematical terms, analysis was usually restricted to mathematical manipulation in the quest to determine the relevance of the theory. Similarly in locational analysis, theories explaining city size and form were tested primarily using mathematical deduction. This classical tradition, although still existing today in various forms and still having some importance, has been largely supplanted by a more conscious process of theory development and testing through modelling, utilising the power of the computer to store and manipulate the large number of observations essential to the process of model design. Apart from the discipline which has come from developing a more explicit scientific method in social science, the computer has also made possible the design of theories and building of models from simple modules whose interaction through replication has produced an added dimension of complexity, commensurate with the mechanisms at work in urban and regional systems.

Although this new analytic tradition represents a breakthrough, it is more exploratory than the old; in some senses, it is less sensitive and less elegant, more ambitious and more straightforward. Its reliance on computation gives it a bias towards the 'number crunching' or 'sledge hammer' approach to theory-building. Yet it has also brought greater opportunities to social science in that many more researchers can participate in the process of theory-building. It has, in short, brought science and mathematics to the realm of everyday affairs. But with these advantages have come a harder, less tolerant evaluation of these new ideas in practice, thus implying that these tools can never be solely valued for their pedagogical use. As this book will hope to establish, a great deal can be learned from urban modelling but one of the dilemmas which will appear time and time again in these pages concerns the content of what is learned. Many critics of urban modelling hold the view that model-builders are learning more and more about their models but less and less about the real world which they are attempting to model. Such a view will always provide food for thought but it illustrates that model-builders walk a fine line between theoretical acceptability and practical feasibility. Outside these narrow limits, respectability is lost and so precarious an existence is perhaps untypical of other fields. Nevertheless, this is part of the challenge which makes this field so exciting and although it is too soon to establish principles for urban modelling, there are some ground rules which dominate the present state of play.

## Ground rules for urban modelling

Simplicity is the hallmark of any good theory and apparent complexity is often simplicity in disguise. Many of the models to be introduced here reflect this observation, and the idea that more complex models can be constructed out of building blocks based on simple postulates, is a theme which is recurrent throughout this book. As far as possible, this rule has been adhered to and it is unlikely that readers will accuse the author of over-complexity, more likely the reverse. A second rule reflects the related idea of parsimony. Simon and Chase (1973) elaborate on this rule in stating: 'If, in order to explain each new phenomenon, we must invent a new mechanism, then we have lost the game. Theories, gradually modified and improved over time, are convincing only if the range of phenomena they explain grows more rapidly than the set of mechanisms they postulate.' This rule of parsimony relates to a further rule based on the idea of using Occam's razor to prune unnecessary embellishments to theories and models which seek to mystify rather than explain.

The rule of clarity is especially important in urban modelling. It is essential to lay bare the assumptions upon which such models are founded for only then can any attempt at objective evaluation be made. Much of the early literature in this field coming from North America is shrouded in mystique. The fact that so much of the early development of the field was pioneered by researchers working in a private rather than public capacity has added further to the confusion, and like many recent developments in social science, these ideas have often been dismissed by social scientists as 'sorcery' (Andreski, 1972) and by physical scientists as precocity. But perhaps the most important rule of all relates to compromise, that quality which removes much of the glamour from both theory and practice. In what follows, there is little mathematical elegance in the classical sense, and little of the pure empiricism which characterises present-day planning and government for such qualities must be impossible to synthesise in any complete sense. Thus, a strong element of pragmatism is coupled with a desire to build strong theory. The strategy to achieve this however has some fairly unconventional turns and it is because of these twists that some apologies need to be offered, especially to mathematicians, in advance.

## Apologies to mathematicians: terminology and notation

The approach to urban modelling adopted here lies toward the end of the spectrum beginning at theory and research and terminating at practice and development. Thus most of the mathematics is of a finite kind with special emphasis upon algorithms, accounting frameworks and some rough and ready numerical analysis. There is little of the more elegant analysis characterising the calculus or statistical distribution theory, although there are small chunks of such analysis generally included in referring readers to other work. This is pragmatic mathematics reflecting a pragmatic approach and those with an eye to formal mathematics may encounter equation systems and explanations which set their teeth on edge. Nevertheless, all of the equation systems given in this book are in a form which makes their programming for a large-scale computer comparatively straightforward without recourse to any intermediate form; at least, all of these equations have been programmed from these descriptions, at one time or another and in various computer languages, by the author.

With regard to terminology, much will be familiar to those working in the fields of statistics and operational research from which a wide variety of terms have been drawn. Hopefully, no new terms have been devised in this book although readers might recognise a North American influence for much of the early work in this field originated in the United States. Terminology is introduced gradually as each idea is developed and definitions are given where necessary. In a similar way, the mathematical notation used is defined when introduced but is constantly redefined to keep the reader continually aware of the problem. An attempt has been made to keep notation completely consistent throughout the book, but because of the very large number of variables and parameters introduced, some redefinition is necessary in parts. In particular, the pre- post- sub- super-scripting of variables has been mainly restricted to the integer range, $i, j, \ldots, n$, and because of the narrowness of this range, certain redefinitions are occasionally necessary. However, key variables such as population, employment, distance, etc. are given a constant notation throughout the book. High-level computer language notation has been avoided.

## An outline of the book

Among the many themes around which this book is organised, the strongest relates to the process of model design reflected in the subtitle as *Algorithms*, *Calibrations*, *Predictions*. Each chapter emphasises specific parts of the process of model design from theory through to operation and prediction in a planning context. Yet there are several subsidiary themes, three of which stand out. The material included in each chapter and the relation of the chapters to one another reflect a very approximate chronological order of research which is also embodied in a second theme concerned with the level of complexity. The material introduced proceeds from the simple to the more complex, a progression which matches the order in which various problems were defined and tackled. For example, this theme involves progression from partial to general, from aggregated to disaggregated, and from static to dynamic modelling. A third theme is less dominant but relates to the phenomena being modelled. An attempt has been made to include models of a wide range of urban systems and subsystems dealing with residential location, shopping, transport and, to a lesser extent, industrial location.

The first chapter is devoted to providing a context for urban modelling and a classification of models in terms of their origins, traditions, early history in North America, and scope. In the second chapter simple models of urban subsystems based on both the generation and allocation of activities are introduced and are assembled into systems of equations for more general models in Chapter 3. In Chapters 4 and 5, the task of getting such models operational is outlined using two examples from the British subregions of Central Lancashire and Nottinghamshire–Derbyshire. But the more important role of these two chapters is to demonstrate how these models can be used in a planning context, in impact analysis and in the evaluation of alternative plans.

Chapters 6–9 are concerned with developing and resolving problems of operational modelling concerning calibration and spatial system design, first identified in Chapters 4 and 5. The problem of calibration is explored tentatively in Chapter 6 using a shopping model, and in Chapter 7, the calibration problem is treated as a problem of non-linear optimisation, demonstrated by shopping and transport models. These calibration techniques are applied to a more general model of the Northampton subregion in Chapter 8 which also serves to introduce problems of zoning and the relationship between the system and its environment which is treated extensively in Chapter 9.

Chapters 10–12 attempt to extend the models of the previous chapters in two ways: by disaggregation of variables such as population and by the design of dynamic models which explicitly treat the concept of time. In Chapter 10, a series of disaggregated residential location models based on explicit ideas about the housing market are developed and tested on the Reading subregion. Chapter 11 sets the context for dynamic modelling by reviewing the concepts involved in making models dynamic and by introducing certain hypotheses relevant to the behaviour of urban systems. Finally, Chapter 12 presents a design for a dynamic model which is explored and tested on the Reading subregion. From these various experiences conclusions are then drawn which comment on the limitations of urban modelling but more optimistically suggest ways in which the potential of urban modelling might be realised in future work.