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Fifty Years of Urban Modeling: Macro-Statics to Micro-Dynamics

Michael Batty

Centre for Advanced Spatial Analysis (CASA), University College London, UK

Abstract
This chapter presents both a chronological and conceptual history of urban land use-transportation models movement in the context of current developments. Such models –'urban models' for short – first appeared in the 1950s in North America and were made possible by two interrelated forces: the development of digital computing from which large-scale simulation emanated, and policy imperatives for testing the effects of large-scale public investments on cities. Essentially, urban models are still pragmatically motivated tools for testing the impact of changes in the locations of land use and transportation on dense and usually large urban agglomerations. Planning and policy determine their rationale although their foundations are built on theoretical ideas which go back to the roots of modern social science and the influence of physics and mathematics from the time of the Enlightenment. During the brief but turbulent years since this field has developed, there have been substantial shifts in viewpoint. Indeed even the paradigms that condition what attributes of the city are to be modeled, and the way such modeling takes place, have changed. We will chart these changes, beginning with a set of intersecting time lines focusing on theoretical origins and practical applications. We will show how urban models were first conceived in aggregative, static terms when the concern was for simulating the way cities appeared at a cross-section in time. This aggregative, static conception of urban structure has slowly given way to one where much more detailed disaggregate activities appear more important and where dynamics rather than statics is the focus. This reflects as much our abilities to simulate more elaborate computational structures and collect better data as any grand theoretical revision of the way we look at the city, although such a revision is now under way As such, this chapter sets a context for many of the current advances in urban modeling reported elsewhere in this book.

1 Historical Antecedents

Wassily Leontieff is best known as the Russian economist who invented the input-output model of the economy in the 1920s before he emigrated to the United States where he subsequently spent his life developing the idea. In contemporary parlance, an input-output model can best be viewed as a large spreadsheet whose rows and columns represent a standard set of components of the economy such as firms or industries and whose row-column entries give the flow of activity in money or materials from one industry to another. In short, it is a 'flow matrix' that mirrors the interdependencies or linkages between every industry and any other. It is useful largely because if we make the reasonable assumption that the flows between any industry and any other are relatively stable and do not change much in the short term, we can use these dependencies to figure out what would happen in all industries if a single industry or a set of industries grew or declined in size. In fact, although the table contains only the direct effects of such change, it was Leontieff's great contribution to show that one could also figure out the indirect effects, thus linking the idea to the 'multiplier' which featured so strongly in the other macro economic models developed at the same time, particularly those of Keynes.

When Leontieff first formulated his model, he knew full well that he would be able to do very little with it unless he had some rudimentary way of automating the many calculations that such tables required, particularly for figuring out the multiplier effects associated with assessing the impacts of change in and on the economy. In the 1920s and 1930s, when he was developing his ideas at Harvard, Cambridge (Massachusetts) was a ferment of activity involving mechanical computation devices in the years just prior to World War II and the invention of the digital computer. He hooked up with Wilbur Eckert at MIT whose simultaneous equation solver looked up to the task of solving linear systems like input-output models which had a large but nevertheless tractable number of equations and unknowns. To understand the imperatives of those times and why Leontieff found it necessary to engage large scale computation to pursue his quest, we must realize that science and technology had caught the imagination of a very wide public and that progress only seemed assured in the social sciences if we could emulate the unholy liaison that had been fashioned between physics and the development of machine technologies.

In fact with his usual eloquence in recalling those times, Leontieff said that when he sat on the rods that formed the frame of the mechanical equation solver, he could actually change the results of the calculations. The rods were associated with the coefficients of linkage in the input-output table, and sitting on them in different positions amounted to changing their weights which in turn physically changed their value! Tweaking the machine implied tweaking the model and this has become the time honored method of testing the sensitivity of our computer models to change. Our point, of course, is less serendipitous. It is that besides theory, computation was all important to such analysis and certainly essential to its implementation, and that urban models would have never begun and would clearly not be in the form they are today without computation. Analogue soon turned to digital and by the 1950s as soon as computers left the lab and entered commerce in the form of mainframes, engineers and policy makers began to think about ways in which digital conceptions of their systems interest could be used for problem-solving and decision-making. Yet there was still a need for theory. Since the late 19^{th} century, there had been rudimentary but nevertheless insightful attempts at articulating how people located in space in analogy to the way particles and forces behaved in physics, with action-at-a-distance the all important underlying foundation for why and how we locate in one place or another. Armed with ideas about how gravitation and potential might condition human location, transportation modeling began in the early 1950s closely followed by its extension to embrace land use.

The history of those times is quite well documented (Batty 1979; Harris and Britton 1985; Wegener 1994) but there are three essential issues that have guided the development of urban models ever since. First and foremost, the key driver for this style of modeling has been policy and planning, not a better theoretical understanding of cities. Second, the computational imperative has driven the way these models have been constructed and the way compromises have been made between different model structures in terms of the availability or otherwise of data. Third, what theoretical development there has been has been *ad hoc*. Unlike economic science where there has been a long and deep quest for a theory of the economic system at both micro and macro levels, urban science has developed more pragmatically. Its contributions have come from wide range of different disciplines, many of these being applications of some wider, different theory usually applicable only to partial aspects of the city system. To an extent, this explains why the field is so volatile, dominated by rather different approaches that are hard to reconcile and imply different paradigms and perspectives on what it is that should be explained and modeled.

In the essay that follows, we will begin by outlining various time lines which are composed of several theoretical and practical developments which chart the history of this field over the last 100 years. Our time lines are based on a classification of the various streams which have influenced urban modeling over the last fifty years which is our prime focus but we must supplement it by inquiring what aspects of cities modelers and policy makers have made their major concern. These, as we shall see, have been 'cities-in-equilibrium' whose structure and dynamics were supposed to be explicable in cross-sectional, aggregative ways and we will begin with these. But this paradigm has been found wanting for many reasons. This more than anything else has changed the focus of our field towards the kinds of dynamics that is represented in the majority of chapters in this book. We will then chart this dynamics but parallel our treatment with a foray into questions of detail, of scale, of disaggregation, and the move towards individualistic explanations of urban location and behavior which link our field to complexity theory from the bottom up. We will then illustrate a couple of examples which identify how these various threads are converging and conclude with some speculation that a new form of social physics is in the making, a social physics that now appears much more promising than the classical thinking of fifty years ago but at the same time, a social physics that intrinsically depends on what has gone before.

2 The Time-Lines: Cities, Planning, Modeling

We cannot produce a timeline for a field such as urban modeling without sketching how this fits within what we know and assume about how cities function in terms of urban theory on the one hand, and land use-transportation planning and urban policy making on the other. To this end we will first sketch three related time lines – one for cities, one for planning, and one for modeling before we then elaborate the modeling line which will preoccupy us throughout most of this chapter. Our knowledge of cities is still largely rooted in the way intellectuals and professionals responded to the growth of the industrial city in the 19th century. By and large, cities were seen as being rather stable structures where the dominant functions were located in some central place, or central business district (CBD) as it came to be known in North America. Growth occurred around the periphery and developments in transportation technologies based on energy in the form of the train and automobile reinforced what had been the mono-centric pattern established in ancient and medieval cities around the market place. Some cities did fuse together forming polycentric clusters, conurbations or 'megalopolis' as coined by Gottman (1957) but the dominant model was that based on the mono-centre.

Within the city – the so-called intra-urban realm – land uses, social groups and wealth-producing activities appeared to invade and succeed each other according to a simple economic logic. This was generally underpinned by the gradual fall in unit transport costs as technologies improved and as activities found they could consume more space on the edge of the city. In the west at least, the industrial city was one in which the poor were displaced in the centre by employment land use activities while the rich moved to the periphery. This archetypal pattern was consistent with the kinds of segregation and relatively homogenous organization that appeared to exist in many places. Per haps the clearest statement was from the 'Urban Ecologists' writing in the 1920s in Chicago who found this pattern to be the one on which Chicago itself had become organized (Park and Burgess 1925).

Urban planning itself had become institutionalized in the late 19th century to deal with urban problems that were occasioned by the growth of the industrial city. Its instruments were mainly ones of locational control – zoning to avoid the worst excesses of pollution, the preservation of open space through green belts which sought to quite literally 'stop the city growing', and decentralization to green field sites in new towns which combined the best of both town and country in terms of quality of life and lower population densities. These strategies contained an implicit reaction against the domination of the single-centered city but to all intents and purposes, they reinforced it by producing new towns and suburbs in the same image, impressing even further the notion that cities should be homogeneously organized in terms of their zoning and land uses. By the 1960s, much of this planning had become explicitly transportation-focused on the provision of infrastructures to keep the pre-industrial urban patterns intact while at the same time engaging in a pattern of urban renewal that reinforced existing zoning. Just as the city was seen as a top-down organization in terms of the way it had developed, so planning as a function of government was also institutionalized from the top down.

Our ideas about cities and about planning began to shift quite radically during the last quarter of the 20th century. First cities did not appear to be the rather well-organized, homogenous, well-behaved places that had often been assumed earlier. Planning, on the other hand, found itself to be increasingly ineffective in addressing any of the key problem-solving it attempted. This was particularly the case for transportation and for public housing where the problems appeared to get worse rather than better as more intervention in the markets occurred. Planning itself came to be regarded as part of the problem rather than the solution. Cities themselves were increasingly polycentric and although the physical focus was still on the CBD, developments in transportation and in information technology as well as changes in patterns of work through the day and the week loosened the ties to the centre. As ever more populations became urbanized and as the agricultural base shrunk to a tiny fraction of employment, cities began to spread out, merge into one another with cross-commuting becoming the order of the day, replacing the traditional movement from suburbs to down-town. All this was set in an increasingly global world where large cities seemed, indeed are often disconnected from their local hinterlands, and even the nations that contained them no longer seemed relevant to their functioning.

In short, cities appeared to be much more volatile, less stable animals than had hitherto been assumed. The notion that they were homogenous and the fact that they should be planned to be so, was increasingly challenged and the idea that they were dominated by simple patterns of movement and transition through time became passé. Planning itself became more participatory in reaction to the fact that top-down implementation was widely seen as destructive and insensitive. All of this is consistent with what we know about complex systems and although the systems approach had been fashionable in thinking about cities and planning from the 1960s on, a switch from centralized top-down thinking to decentralized bottom-up began to occur on every dimension. The very notion that there was something called a city and something called planning was up for grabs. ‘Edge cities’ emerged in many parts of the world – cities around cities, and cities within cities – while forecasts that we would all be living in cities by the end of the 21st century, polarized the crisis as to what a city ‘actually’ was. Our whistle stop tour of the 20th century history of planning and cities is encapsulated within two of the time lines in Fig. 1, but our real focus here is on the kinds of theory and knowledge that was used during these years to fashion the development of urban models that could be used to both explain and predict as well as help inform prescriptions for future cities. It is to these that we now turn.

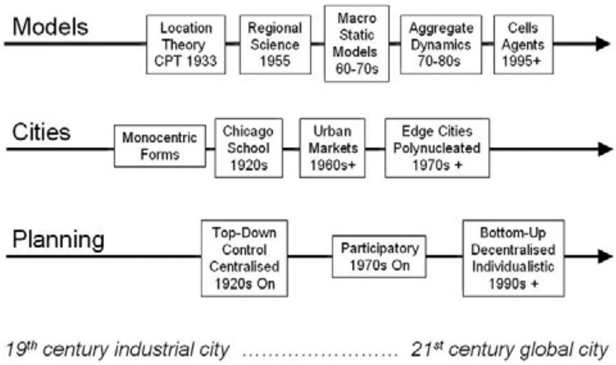

Fig. 1. Intersecting time-line

The theories that were used to underpin our understanding of cities and the various tools that were fashioned to explain and predict their future form closely reflected the top-down, relatively stable, equilibrium-dominated views of planning and cities that we have briefly sketched. Three key ideas of explanation, each based on the notion that it was the cross-sectional structure of cities that should be explained, developed from the late 19th century which we can christen 'economic location theory', 'social physics', and 'geographical/spatial morphology'. Location theory emerged somewhat idiosyncratically from the German School in the late 19th century although it was preceded by ideas about rents and markets in the rudimentary economics of Von Thünen and Ricardo in the early part of the same century. This theory essentially argued that industries located according the balance between their spatial patterns of demand and supply while its generalization to populations sought to show how cities were structured hierarchically from the largest to the smallest according to demand in their hinterlands for the services they provided. This was central place theory developed by Christaller (1933, 1966) in the 1930s and linked to industrial location theory in a coherent economic framework by Losch (1943, 1954) some ten or so years later. It established inter-urban theory based on the idea that systems of cities were also organized spatially as overlapping hierarchical fields while it was picked up by those concerned with the shape or morphology of cities which constitutes our third theme.

Social physics has a longer tradition in that, ever since the late 17th century, there were many ad hoc attempts to apply classical mechanics in the form of Newton's Laws of Motion to the strength of relationships between people and places at different scales from cities to local neighborhoods (Ball 2004). These were consistent with much of location theory which came later particularly when these theories were treated aggregatively, and it also provided some essential tools to measure proximity, accessibility and to simulate movement between places. The earliest attempt was by Ravenstein who used the gravitational model to explain migration flows in the late 19th century in Britain. It is not the purpose of this chapter to detail the entire history of these movements but readers who wish to get a sense of this theory should look at Isard's (1956) book *Location and Space Economy* which summarizes all these developments as well as laying out the foundations for regional science that was the bandwagon that pulled all these ideas together in the years following World War 2. Our third theme on geographical/spatial morphology contains both elements of location theory and social physics but the concern is more descriptive, examining ways in which the city is structured. It has been based on the search for patterns in a geographical sense, and generally this corpus of theory has been the domain of urban geographers useful in an operational sense for focusing ideas on what to model rather than how to model the phenomena (Mayer and Kohn 1959).

Once the momentum for fashioning these ideas into tools for urban and transportation planning was established in the 1950s, three distinct sets of techniques emerged to be used as the nuts and bolts from which simulation models were thence developed. Social physics provided the rationale for gravitational models which were used to simulate all kinds of transport flow while micro-economic theories in which the location of individuals and firms could be simulated inside cities as a function of their demand for space, their incomes and their transport costs, were rapidly developed. In this sense, rents and other costs in cities were shown to be inversely related to transport cost or distance, again linking these to the entire gamut of social physics models which were dominated by action-at-a-distance. Models based on the application of macro-economic ideas to the space economy, largely the prerogative of regional science in the form of spatial input-output and econometric forecasting, were also developed, into which more spatially disaggregate models could be embedded. There is no single source covering all these techniques although the book by Isard (1956) and his various successor books cover much of the field while a good summary of ideas from the urban economic standpoint is contained in the book by Fujita (1989) *Urban Economic Theory*.

This then was the context for quite radical changes in urban theory which emerged during the last 25 years of the twentieth century. First, the fact that this entire panoply of models and techniques fashioned around micro-economic theory and social physics treated the city as if it were in equilibrium was questioned from the start. As our collective and documented experiences of how cities change became more complete, it was quite clear that it was growth and change, behavior rather the structure, that was a more appropriate focus for explanation. Second, the notion that surprising things happened in cities had been relegated to an appendix in earlier work but it now appeared that the condition of cities that planning should address is much more bound up with innovation, creativity and surprise than with homogenous land use structures. Third, the idea that cities emerged not from any top-down action but from the bottom up, forced theoreticians and model builders alike to think about emergence, about modeling systems as individuals, not collectives of population and employment. Macro thus moved to micro and static to dynamics. Fourth, the idea of scale came onto the agenda with much planning being concerned more with the small than the large scale. All this was set against massive changes in the computational power and data resources available to those whose concern was urban simulation. Aggregative dynamics dominated developments in the 1970s and 1980s, and by the early 1990s under the inspiration of complexity theory, urban models based on cells and agents began to appear alongside the long-standing, aggregative, static models of the 1960s. It is now time to unpack these developments in more detail and deconstruct our urban modeling time line shown in Fig. 1 above.

3 Deconstructing the Urban Modeling Time-Line

We could spend this entire book showing how these various time lines can be elaborated, how they emerge, merge, and diverge, how they coalesce and how the key contributors move from one style of theory and model to another. But let us first fine-tune our three perspectives on cities in terms of location theory, social physics, and geographical morphology. As we indicated these three approaches are quite consistent with one another for they reinforce the aggregative, cross-sectional, non-behavioral, non-dynamic view of cities in terms of the theories and their models that we sketched above. But to take our history further we need to show how these foci have provided the momentum for developing much more dynamic, bottom-up disaggregate models of cities which now form the cutting edge of this field and dominate the contributions in this book.

Our urban modeling timeline can be constructed as a composite of these three themes, each representing a line in its own right. Key 19th and first-half 20th century statements of location theory and their subsequent elaboration into regional science and then urban economics are first rooted in the work of Johann Heinrich von Thünen in 1826 in his *Der Isolierte Staat in Beziehung auf Landwirtschaft und Nationaloekonomie*. For social physics, we take Walter Christaller's *Die Zentralen Orte in Suddeutschland* in 1933 as the starting point and for spatial morphology we root this in George Kingsley Zipf's *Human Behavior and the Principle of Least Effort* published in 1949. These origins might seem somewhat curious in that Christaller is often associated with location theory and Zipf with social physics. But it is current developments that we have in mind when we make these choices. Location theory remains the purest of these origins for theory rather than modeling, and simulation where social physics remains the focus of this genre. In morphology, theory too remains the focus with an emphasis on aggregative patterns and shape where ideas are used to describe rather than simulate and where the concern is with the physical-spatial properties of cities and regions. It is in the work started by Christaller from which operational models have emerged for it is here that a concern with pattern and analysis, with only looser links to economic processes and aggregative spatial properties, dominate. In short, this second theme is the one from which operational urban models dating back to the 1950s and 1960s. originate although recent developments fuse these traditions in quite subtle ways.

The idea that theory from one or more of these lines is then used in another or the same tradition to design, build and use an operational urban model (which is essentially a computer simulation) is short of the mark. Individuals associated with these traditions rarely move from one line to another although the influence of the ideas across these themes is strong. Occasionally location theorists have developed optimization models which focus on facility location or urban economic models which link to policy but this is largely because this field is influenced by urban planning and public policy. In contrast, those working in spatial morphology are in more descriptive, less problem-solving oriented traditions and thus most of the models developed in this tradition are largely non-policy-oriented, hence non-operational. Urban models which we will associate with the social physics theme emerged through policy imperatives largely in terms of the coming together of requirements for solving transportation problems in cities in the context of rapidly developing computer technologies which made simulation possible. In the 1950s, social physics ideas were very much in the air and modeling began with the use of the gravity analogue used to simulate flows between origins and destinations where distance or travel cost was the key organizing device reflecting action-at-a distance as implied in central place theory and the rudimentary geography of retailing. By the late 1950s, many of these models were available and hard on their heels came extensions to embrace the location of land use (Voorhees 1959). The watch word of the 1950s in urban planning was that 'transport was a function of land use' and the idea of relaxing trip ends to embrace locational predictions was soon adopted. A flurry of operational models developed in the 1960s culminating in the landmark issue of the 1965 *Journal of the American Institute of Planners* edited by Harris (1965) which represented an excellent early summary of the state-of-the-art.

Most of these early models represented a fusion of social physics ideas with rudimentary regional economics as developed within regional science, the most developed exemplar being Lowry's (1964) *Model of Metropolis*. A variety of simulation techniques were used, ranging from relatively sophisticated econometric analysis to simple event-based simulation. Location theory in so far as it was consistent with gravitational and regional economic modeling, was important but most of the developers of these models, although aware of such theories, did not consider their role as being to implement such theory. Models were built for the purpose at hand against this known but implicit theoretical backcloth. There were some places where there was an appeal to more detailed theory. For example at the University of Pennsylvania in the early 1960s, Alonso's (1964) theory of the housing market which was one of the forerunners of urban economic theory was used to structure a variety of operational models developed by Britton Harris all set against the background of developments in regional science at Penn as well as forming links to new models in the social physics tradition. The same kinds of concern for incorporating economic processes were developed by Kain and his associates at Harvard and although both these developments were inspired by real policy-making, the models were rarely applied in practice (Ingram et al. 1972).

What came out of this experience was a consolidation of techniques with a concern for linking operational models to theory. There was a general feeling amongst theoreticians and model-builders that what was required was much greater consistency concerning model structures and there was a general move to make models ever more comprehensive, embracing more and more urban sectors at ever more spatial and sectoral detail. For example, in the UK, Wilson (1970) and his colleagues attempted a grand synthesis based on spatial interaction theory which was made consistent using entropy-maximizing analogies with thermodynamic systems in equilibrium. These were also interpreted as part of a wider theory of optimization in which supply and demand within various urban markets could be reconciled with spatial interactions (Wilson et al. 1981). At this time, much stronger economic foundations were laid for such models within discrete choice theory based on utility maximizing (Ben Akiva and Lerman, 1985) while there were attempts to cast these structures within some wider economic equilibrium.

Yet despite the optimism of the 1960s, this was quickly followed by reaction against when models were found wanting along several dimensions. First, in terms of urban planning and policy-making, the models did not address the actual needs for decision support posed by the planners. In short, many models and their model builders sought to answer the wrong questions. When the questions were the right ones, invariably there were arguments over their robustness, given the open and uncertain nature of social prediction while quite often the planning context was so volatile that the very questions changed while the models themselves were still under construction. This was not a good beginning. Combined with the cost of such models and the lack of data along with the fact that this entire domain was being invented on the job, so-to-speak, it is not surprising that the field virtually went into hiding as model-builders retreated to reflect on the experience and nurse their wounds. Lee's (1973) 'Requiem for Large Scale Models' published in the *Journal of the American Institute of Planners* epitomized the vitriol of the reaction.

Those who were reflecting on the models themselves were well aware that cities were much more volatile and heterogeneous affairs than had been assumed hitherto. There was something inconsistent about a domain such as planning which engendered change using models that assumed that the system of interest could move quickly to equilibrium. This was the nature of the theoretical critique but the key problem in articulating models and theories that dealt with urban change rather than urban structure involved our woeful ignorance of urban processes. Moreover the data problem which had plagued the first modeling efforts was doubly severe when it came to thinking about simulating dynamics. Whereas spatial structure was understood to some extent, dynamic structures were much more problematic with little coherent knowledge about how they manifested themselves in cities and certainly little idea about how they impacted on spatial structure. Model builders were forced to look elsewhere for such ideas and as usual it was to physics and mathematics, rather than to the social or biological sciences, that they turned. At much the same time, there were various developments in mathematics focused on rapid and discontinuous change, incorporating radical, qualitative change that became popular. Ideas about how cities could manifest such discontinuous change were examined with catastrophe and bifurcation theory becoming fashionable. When chaos theory became established in the 1980s, these efforts were extended to examine chaotic cycles in urban phenomena. In fact this foray into aggregate dynamics did little for operational modeling which was slowly recovering and adding its own version of urban dynamics by simply repeating cross-sectional models at different cross-sections in time. In short by the mid 1980s, the field consisted of the models of the 1960s improved to deal with greater detail with the addition of some quasi dynamics but still being essentially dominated by cross-sectional aggregative statics. In terms of theory, the many forays in aggregate radical dynamics simply served to show how one might proceed but there were few, if any, applications that were developed in practice

From the mid-1980s, however, a sea change began which was not anticipated, indeed had even been regarded as being inconsistent with the way one should theorize about and model any system. It had long been felt that the law of large numbers was an essential underpinning for all science; but what has gradually happened over the last 50 years is a relaxation of these canons of science. When knowledge is always regarded as contingent and never certain as the case with land use-transport models, and when our ability to steer and manage cities is increasingly in doubt, then the structure of a scientific theory that is based on parsimony and generalization comes under severe scutiny. In short, if the models could not predict anyway, then perhaps the focus should be on building models that informed, extended our understanding, focused us on key issues, but were rich enough to address the questions at hand. Modeling thus began to resemble pedagogy more than prediction, to resemble 'story telling' (Guhathakurta 2002) rather than to provide a definitive understanding of the system of interest and what might happen to it.

In a sense, this sea change in our thinking was paralleled by wider moves to limit the power of government as the grass roots began to reassert itself. Moreover as populations became wealthier, as technologies pervaded all corners of society, then individuals became enfranchised in a way that was very different from the condition of industrial society in the 19th and early 20th centuries. Basically centralization gave way to decentralization with computing technologies and the net being the most potent symbol of this change. In terms of modeling, the focus shifted from aggregates to agents, from groups and collectives to individuals, from large spatial neighborhoods such as census tracts to cells or land parcels, as the quest to model everything in more detail gained the ascendancy. At the same time, the idea of how individuals behaved and their cognition of location and space became more central to the new model styles that emerged. Agent-based modeling and its physical counterpart in cellular automata, as we will discuss in the next section, gradually gained ground but with a very different constituency from that on which the earlier experiences were based. These models are much less rooted in policy and practice and tend to much more speculative than their earlier counterparts. They deal with intrinsic processes of change and in this sense are explicitly disaggregate and dynamic. They embody ideas about how spatial structures might emerge and they have the potential to deal with surprise and innovation. They represent a new way of thinking about cities.

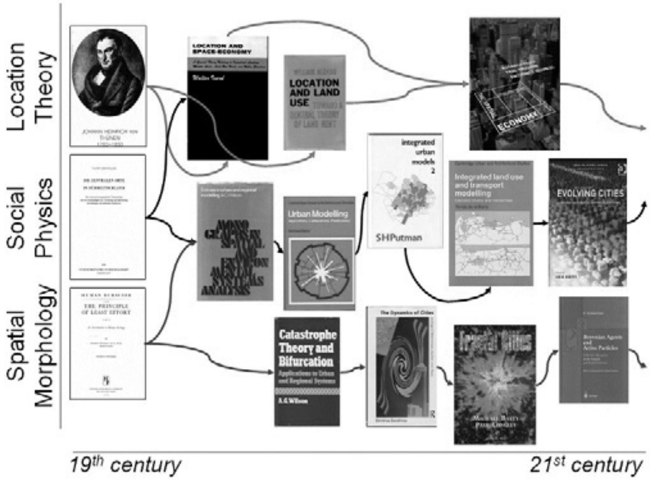

Fig. 2. Snapshots along the urban modeling time line

In parallel to this as our time line implies, the properties of cities have been explored spatially in terms of their morphology through ideas about form and structure using new ideas from geometry (Batty and Longley 1994). The early social physics has also coalesced with these developments and more recently new developments in statistical physics have begun to suggest ways in which cities and related systems can be simulated from the bottom up (Schweitzer 2003). These approaches are beginning to influence operational models as are developments in location theory which incorporate spatial interaction and emergence through growth and trade theory (Fujita et al. 1999). We sketch rather impressionistically these three time lines in Fig. 2 using key statements to identify the stages along the way. These are but snapshots of what has been happening during the period and there are many other similar statements. But this does set the tone for many of contributions in this book where physics-based approaches are rapidly gaining ground as the theoretical rationale for interpreting a variety of structures consistent with these new approaches to simulation.

Before we complete this section, we should not forget that there is also a new wave of land use transportation models – urban models –built around the earlier tradition but being influenced to a degree by these new developments. Many of these models are rooted in behavioral spatial interaction theory and have embraced the agent-based approach but are still largely static in structure, rather than temporally dynamic. Such models are fashioned around developments in transportation modeling and have successfully incorporated new developments in data and GIS in the way they are being constructed (Maguire et al. 2005). There is no real convergence of styles as Fig. 2 implies, nor should there be as different traditions continue to inform one another. But what is clear is that 50 years on from the time when urban models were first applied in the mid 1950s, we now face a much richer but also much more uncertain style of modeling where the focus is less on predictions, more on understanding and informing. It is to this that we now turn.

4 The Quest for Dynamics: The Macro Perspective

It is hard to know quite why certain concerns and fashions arise in any field and although the quest to make operational models dynamic was widely felt, what began to emerge in the 1970s was quite counter to the most obvious dynamic extensions to existing models. In the 1960s, almost from the inception of land use modeling, some efforts were made to add dynamics by repeating the cross-sectional logic at different points in time but the data problem and the need to produce equilibrium predictions did not elevate this concern to the fore. The first and most dramatic foray into dynamics came from another source. In 1969, Jay Forrester who had applied his ideas about machine dynamics to the firm in the form of industrial dynamics, in talking with the Mayor of Boston, decided to apply his simulation models to the decay of the inner city. What resulted was a model reported only once in his book *Urban Dynamics* (Forrester 1969) but reported in such a way that it made a remarkable splash. Here for the first time was a fully-fledged dynamic model of the city based on the logic of feedback but devoid of any spatial variation whatsoever. This was greeted by the establishment with horror and while it was largely ignored in terms of empirical applications, it did represent a clear statement which others began to emulate in thinking about making the now conventional models dynamic (Batty 1971).

What actually happened in terms of developing ideas about urban dynamics came from elsewhere and in so far as this could be traced to any distinct movement, it came from mathematics, specifically catastrophe theory which had gained the public imagination after Rene Thom published his book *Structural Stability and Morphogenesis* on the subject in 1975. The idea that cities were full of discontinuous change was pursued by Wilson (1981) who largely fashioned his extensions to spatial interaction models in a framework which relied upon non-linear logistic growth, leading to rapid change characteristic of some urban phenomena such as the growth of edge cities and shopping malls. In contrast, Allen (1997) developed Prigogine's ideas associated with reversible thermodynamic systems which illustrated that low-level (local) random change could divert the city's growth path onto very different trajectories, impressing the idea that the actual growth of any city was simply one from an infinite number of possible futures. His model was applied somewhat casually to Brussels while the Wilson models were more focused, particularly on the emergence of retail centers. There were no empirical applications, however, which informed policy.

This concern for dynamics was picked up in the United States as Prigogine and Allen's work was funded by the US Department of Transport and this provided a focus for further work. For example, Dendrinos developed various ideas about dynamics built around coupled non-linear equations of the form used in predator-prey models generating various evolutionary models of the city system at different scales (Dendrinos and Mullaly 1985). His models although empirically tested, were not applied in a practical problem-solving context with much of the work spinning off from these attempts tending to focus more on theory than practice. Although there was considerable momentum with respect to discontinuity in urban dynamic modeling, this tradition although relating to operational urban models and involving many people with direct links if not experience of building and applying those models, diverged from practice. There were very few attempts at incorporating these ideas in practice. Although the ideas probably made an impact insofar as they alerted the field to the importance of dynamics, the fact that 'cities-in-equilibrium' was not their dominant focus.

By the late 1980s with chaos theory and its relationship to fractal geometry becoming well-known in the sciences, there were various attempts to see such theory as forming a dynamics of city growth and change, following the rather tantalizing possibility that population dynamics could in principle and possibly even in practice lead to chaotic cycling from quite deterministic origins. This gave further weight to Allen and Prigogine's idea that urban growth at the very bottom was essentially dictated by initial conditions that could never be pinned down and that the intrinsic unpredictability of such complex systems was something that should be faced. 'Sensitivity to initial conditions' became the watchword. Dendrinos and Sonis (1990) for example, incorporated much of this theory into their speculations about the dynamic behavior of spatial systems while Nijkamp and Reggiani (1992) provided a useful summary of the state-of-the-art. However, while supporting the general field, this excursion into macro dynamics simply provided a backcloth for discussion and speculation, and did little to extend the art of operational urban modeling useful to policy-makers.

Although the traditional, aggregate, cross-sectional models which formed the origins of the field had been pushed out of practice, this was not for long. Transportation problems in cities and the explosion of urban growth in terms of sprawl was never very far away and some of the key models associated with Putnam (1991) at the University of Pennsylvania, Echenique (1985) at Cambridge and Wegener (2004) at Dortmund continued to be developed. Attention was paid to extending such models to incorporate the local economy in terms of spatial input-output models, interfacing them to more sophisticated discrete-choice spatial interaction transportation models built around the classic four stage process. Disaggregating the model variables also reflected more detail and greater diversity. The notion of repeating the cross-sectional simulations through time was made more transparent, largely because prediction had always been the goal of those modeling efforts. By the 1990s, a reasonable arsenal of practical modeling tools for transport planning and urban growth was available. In fact in the 1980s, a comparative study of several of these modeling efforts in which different models were tested on a standard set of data bases was attempted in the ISGLUTI project (International Study Group on Land Use Transportation Interaction) and although the comparative analysis was limited, this study did detail many of the pitfall and hidden assumptions in constructing and applying such models (Webster et al. 1988).

There were very few new modeling efforts in the original tradition developed during these years but three are worthy of mention: UrbanSim developed by Waddell (2002), the California Urban Futures (CUF) model by Landis and Zhang (1998), and Anas's (1982) residential model based on urban economic markets and transportation choice theory. Waddell's model is the most complete and it alludes to many new ideas in modeling urban systems, has well-developed urban economic and transportation components and is quasi-dynamic. Anas's model is not dissimilar although it is restricted to the residential and transportation sectors, while Landis and Zhang's model is focused on the land development process. Recently there have been quite impressive attempts to link several of the key operational models to various kinds of environments and evaluation indicators. In the EU SPARTACUS project and its follow-up PROPOLIS, traditional model structures are being extended to embrace GIS through common interfaces for the MEPLAN, TRANUS (de la Barra 1989) and Dortmund Models (Spartacus Consortium 1998; Propolis Consortium 2004; Wegener 2004). Currently there is added interest in traditional models as many of them have painfully struggled to embrace new technologies and ideologies while keeping their operational focus.

5 Towards Micro Dynamics: Agents, Cells and the New Social Physics

Somewhere along the way, new currents have emerged from both within the field and without. From within, the focus began to change due to the existence of new data sets and new technologies such as GIS and a new generation of physical models have appeared. These attempt to simulate the development process in terms of urban growth, building on simple ideas about diffusion as in cellular automata (CA) modeling. This has been paralleled by a concern for even finer-scale disaggregation for simulating populations at their most individualistic level. This is not micro-simulation in the traditional sense as it has been used in social and urban simulation (Clarke 1996) but the representation and simulation of individual agents in terms of their preferences and movement patterns. These agent-based models are much wider than urban simulation *per se*. A lot of social science and some physical science have been pervaded by the 'agent-based' viewpoint largely because computer systems and fine-scale data have made such representions possible. Agent-based models, in a sense, are being informed from without although geodemographics – the study of fine scale population profiles at a highly disaggregate group and spatial scales – is forcing their development.

The wider context for both cellular automata modeling of urban development processes and agent-based models of urban movement and change clearly reflects a new view of systems theory – complexity theory – which has shifted the long-lasting concern for the city as a system from its structure to its behavior. Dynamics has come back firmly onto the agenda embracing not only the macro-dynamics of discontinuity discussed above but also micro-dynamics posed by individuals operating from the bottom up. This shift from the top-down has occasioned much speculation about cities being emergent systems where the structures evolved are often novel and surprising, thus relating to Allen and Prigogine's ideas about urban futures which were first spelt out two or more generations ago. At the same time, there has been a flowering of new ideas and techniques in statistical physics. In particular the notions of critical thresholds and of systems far-from-equilibrium have gained much ground while new techniques to study diffusion and the growth of network structures has fashioned a new generation of models which might be said to represent a new social physics (Schweitzer 2003, Batty 2005a; Andersson 2005). From a rather different angle has come a new view of the spatial economy which is closely linked to many of these ideas in the new physics where dynamics, movement and trade are central (Fujita et al. 1999). In essence, what these new theories are providing is a coherent set of ideas about dynamics at the individual as well as collective level with clear links to the spatial morphologies generated, and linked in various ways to long standing traditions in location theory and urban economics. Everywhere one looks, there are concerns for merging these various traditions as Fig. 2 implies. Indeed at this point in time, there is a great melting pot of ideas being used to construct different perspectives on the urban system.

Very few of these models are operational in the traditional sense. But in a way, this is consistent with the retreat from prediction that has become more acceptable even in a practical context where the need for discussion of the urban future is still as urgent as ever. Modeling as story telling, as pedagogy, as informed speculation, has become the rationale for the development of these new ideas and it is still too early yet to see how it will all pan out. The chapters in this book are as significant as barometer as we currently have. To conclude, let us focus a little on those models which are closer to operationality and we will take cellular automata as our exemplar. Cell-based models in analogy with CA were suggested for urban growth as far back as the early 1960s and in that tradition, the models developed by the Chapin and Weiss (1968) in North Carolina and by Lathrop and Hamburg (1965) in Buffalo, NY are noteworthy. In 1970, Tobler developed his own simulation of the growth of Detroit and through the 1970s, he speculated on how cell-based ideas might be used to simulate diffusion in local spatial neighborhoods (Tobler 1970, 1979). Couclelis (1985) continued this tradition in the 1980s and the growth of GIS gave the area a push with raster-based data sets often being used for cellular representation. What is noteworthy about this emerging tradition is that it is not really strongly linked to operational land use-transportation modeling expect through individuals who have worked on both or been associated with both. It is mainly geographers who have developed CA models and their focus has been almost entirely physical. The major critique of this work relates to the absence of an urban economy underpinning most of the models, and the somewhat cavalier approach to action-at-distance which is subsumed within local neighborhood effects and transitions. By and large, transportation is missing from these models. Where these limitations have been relaxed, the models appear quite close to some of those developed 40 years or more ago.

Very few of these CA models have been developed for practical policy applications. Batty (2005b) provides a list of the main groups working in this area. The two that have got closest to practical applications are the Santa Barbara group (Clarke et al. 1997) and the group led by White and Engelen (1997) at RIKS. Both groups have developed hands-off type policy applications mainly for regional and national agencies: the Santa Barbara group for urban growth in the US for USGS (United States Geological Service) while the RIKS group for the European Commission. Again where the model structures are relaxed, they come closer to the traditional corpus of land use-transportation models. There are now probably upwards of 50 such applications world-wide but most exist in academia and relate more strongly to the new traditions in complexity theory and social physics than they do to the ongoing urban modeling tradition. In terms of the development of agent-based equivalents, although there are many partial models of urban sectors dealing with processes such as residential segregation, pedestrian movement and so on, there are hardly any constructed for urban development. These are of course in their infancy and it is entirely possible that in the next decade there will be attempts linking the largely non-spatial micro-simulation of cities to their spatial equivalents which will be agent-based. Several of the chapters that follow imply these developments.

6 What Has Been Achieved: Retrospect and Prospect

One of fascinating features of this 50 year history is that most of the people who contributed to it are still alive and if not working within it, are conscious of how it has and is developing. Although we have sought to show how different lines of development have been generated spontaneously or have emerged naturally from developments so far, bringing in new people or developing the expertise of those already in the field, the field is still quite narrow and relatively focused. As one moves more towards practical applications, there is less concern for new theoretical developments but as urban models are still so idiosyncratic in their design and construction, most model builders have to be and are indeed aware of the general state-of-the-art. In this sense, the field is still coherent and tight; it is the context that has changed. The models built 50 years ago were constructed on-the-fly, so-to-speak, in practice, and when viewed form the vantage point of the early 21st century, it was something close to a miracle that they worked at all. In perspective, although the experience was salutary and the first generation of models and modelers were exposed to a baptism of fire, the field continued largely because the policy problems that motivate the need for a better understanding of cities and the need to predict the future have not gone away.

What has changed is our perspective on what is possible. Simulation itself is no longer just about predicting the right future but about predicting many futures. Modeling is about story telling, about informing us of many possible futures. And all this is consistent with the notion that cities and the societies they are a part of are intrinsically complex and inherently unpredictable. The question as to why we still need predictive models in this context is still not resolved for there are many who still consider that this way of thinking is a luxury society cannot afford. But slowly and surely, the view is gaining ground that the informed speculation that such simulation clearly brings and the ability to communicate this through models is a valuable focusing activity; and if only for this, many practical agencies mandated to grapple with urban problems accept the need for this style of modeling. In short, what has emerged is a hierarchy of model types, and it is fitness for purpose that is now the distinguishing mark that must be applied when considering applications. These themes are picked up time and again in the chapters in this book. The conundrums and paradoxes of a complex urban world will always remain but our ability to handle them is surely informed and extended by the new generation models presented here.

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