# Operational Urban Models

## State of the Art

Michael Wegener

**Twenty years after Lee's "Requiem for Large-Scale Models," the urban modeling field is again full of life. There exist a dozen or so operational urban models of varying degrees of comprehensiveness and sophistication, which have been and are being applied to real-life metropolitan regions for purposes of research and/or policy analysis. The paper views the current state of the art of operational "integrated" urban models. It starts by presenting the map of active centers of urban modeling research in the world. Next it defines a framework for the classification and evaluation of urban models, using as criteria comprehensiveness, overall structure, theoretical foundations, modeling techniques, dynamics, data requirements, calibration and validation, operationality, and actual and potential applications. The paper closes by speculating about the most promising avenues to further improvement and diffusion of this kind of model.**

Wegener is Deputy Director of the Institute of Spatial Planning at the University of Dortmund, Germany. He started to develop his first urban simulation model in 1969 and has since always been involved in urban modeling. He was a member of the International Study Group on Land-Use/Transport Interaction (ISGLUTI) and is a Co-Chairman of the Special Interest Group "Land Use and Transport" of the World Conference on Transport Research.

*Journal of the American Planning Association,* Vol. 60, No. 1, Winter 1994. © American Planning Association, Chicago, IL.

The diffusion of successful ideas and products tends to follow the familiar S-shaped curve from pioneering via take-off and mass adoption, to market penetration and saturation (Rogers 1962). This can be seen by noting how faster transportation technologies such as the railway or the car superseded their slower predecessors (Marchetti 1987) or how new information technologies such as the telephone or the fax machine conquered their markets. The computer, in particular the personal computer, is now in the stage of mass diffusion; and the recent boom in geographical information systems demonstrates the universal validity of the innovation-diffusion paradigm of product life cycles.

The idea that computer models of urban land use and transportation might contribute to more rational urban planning was born in the 1950s and culminated in the 1960s. The 'new tools for planning' (Harris 1965) were thought to be a major technological breakthrough that would revolutionize the practice of urban policy making. However, the diffusion of urban models faltered soon after the pioneering phase, for a variety of reasons. Batty's and Harris' papers in this issue (Batty 1994; Harris 1994) give a broad account of some of them. The most fundamental probably was that these models were linked to the rational planning paradigm dominant in most Western countries at that time. They were perhaps the most ambitious expression of the desire to 'understand' as thoroughly as possible the intricate mechanisms of urban development, and by virtue of this understanding to forecast and control the future of cities. Since then the attitude towards planning has departed from the ideal of synoptic rationalism and turned to a more modest, incrementalist interpretation of planning; that has at least co-determined the success or failure of large-scale urban models.

In his "Requiem for Large-Scale Models," Lee (1973) notes the widening discrepancy between the models and the changing planning context and is not surprised that the models failed to respond to the new developments, because they "symbolized the last offensive of the technocratic, hypercomprehensive mode of planning" (p. 172). But having been involved in modeling himself, his critique of the models is that of a rationalist and a modeler. His "seven sins of large-scale models"—that the models were too comprehensive yet too gross to be useful for decision makers; that they required huge amounts of data but contained little theoretical structure; and that they were complicated, mechanical and expensive—seem from today's perspective rather ephemeral and in part rendered irrelevant by twenty years of progress in theory, data availability and computer technology since the publication of his paper.

Nevertheless, as a piece of forecasting, Lee's paper has been remarkably successful. Nowhere in the world have large-scale urban models become a routine ingredient of metropolitan plan-making. Pioneering pilot projects were abandoned or simply shelved. The modeling pioneers either turned to other, more recognized fields of activity or retreated to the basements of academia, where some of them were able to find a niche to continue to polish their models. Lee's influential paper may even have helped to make its forecast come true. Anecdotal evidence of this is my own experience of enclosing a copy of the "Requiem" with a proposal for a modeling project for the City of Düsseldorf. Many years later I was told that this honesty had contributed to the proposal's being turned down.

Yet despite the lack of broad success, twenty years after the "Requiem" the urban modeling field is again full of life. There exists a small but tightly knit network of urban modelers dispersed across four continents. There exist a dozen or so operational urban models of varying degrees of comprehensiveness and sophistication that have been and are being applied to real-life metropolitan regions for purposes of research and/or policy analysis. And there exist, at this very time, exciting opportunities to incorporate new theoretical developments and methodologies into the field.

The paper aims at an overview of the current state of the art of operational "integrated" urban models. It starts by presenting the map of active centers of urban modeling research in the world. Next it defines a framework for the classification and evaluation of urban models, using as criteria comprehensiveness, overall structure, theoretical foundations, modeling techniques, dynamics, data requirements, calibration and validation, operationality, and actual and potential applications. It is shown that most of the criticisms of the "Requiem" have been taken account of by today's modelers or have been made redundant by advances in data availability and computing technology. The paper closes by speculating about the most promising avenues to further improvement and diffusion of this kind of model.

## The Map of Urban Modeling

In a recent commentary, Couclelis (1993) associates urban models with late modernism and concludes that their time has passed and that the number of urban modelers is "shrinking fast," whereas GIS are associated with postmodernity and hence are growing. Her conclusion about the number of modelers, at least, is not in line with reality. In fact the number of real-world applications of urban models, while it has not grown as rapidly as originally expected, has increased steadily over the last decade. There are more than twenty university laboratories, public agencies or private firms on four continents where research and development in urban modeling is actively being conducted, and there are a dozen or so operational urban models of varying comprehensiveness and sophistication that have been or are being applied to real-life metropolitan regions for research and/or policy analysis.

In this section, the geographical distribution of contemporary urban modeling research is presented. Figure 1 shows the map of active urban modeling centers in the late 1980s and early 1990s and the names of their principal researchers. The map is based on available evidence from the modeling literature and on personal communications.

Before proceeding, it is necessary to define the types of urban modeling projects considered in this paper. The first distinction is that the term model is used here to indicate *mathematical* models implemented on a computer and designed to analyze and forecast the development of urban systems. This excludes qualitative or hermeneutic representations of urban theory irrespective of whether they can be empirically tested. The second distinction is that the models must be *comprehensive*, i. e. they must integrate the most essential processes of spatial urban development; this implies that they must include at least urban land use and transportation, where land use denotes a range of land uses such as residential, industrial and commercial. This excludes partial models addressing only one urban subsystem such as transportation, housing or retail. Furthermore, the models must be *operational* in the sense that they have been implemented, calibrated and used for policy analysis for at least one metropolitan region. This excludes models presented only in theoretical terms as a set of equations.

The twenty centers in Figure 1 are numbered from west to east and are associated with the following individuals and modeling projects (in some cases two centers in one metropolitan area are grouped together):

1 *San Francisco.* The Bay Area is the home of two modeling groups. Prastacos' (1986) Projective Optimization Land Use Informations System (POLIS) of the San Francisco Region, developed for the Association for Bay Area Governments, is one of the few urban models developed outside a university. The model is a sophisticated mathematical programming formulation of the Lowry Model (Lowry 1964) based on random utility and incorporating the location of basic employment. The other model, CUFM, the California Urban Futures Model (Landis 1992; 1993), a successor to the classic BASS (Goldner 1971), was developed at the Institute of Urban and Regional Development of the University of California at Berkeley as a disaggregate model of housing development, and is one of the first urban models to utilize geographical information system (GIS) technology.

2 *Urbana.* At the Department of Civil Engineering of the University of Illinois at Urbana-Champaign, Boyce developed nonlinear programming equilibrium models of transportation and location (Boyce, et al. 1983; 1985; Boyce 1986). Since Boyce's move to Chicago, this tradition has been continued by Kim (1989) and Rho (Rho and Kim 1989) with combined models of transportation and location in the Chicago region incorporating goods movements.

3 *Chicago.* The "best studied city in the world" has been modeled in econometric housing market, land use and transportation models by Anas at Northwestern University (Anas 1982; 1984) and also, using the Chicago Area Transportation and Land-Use Analysis System (CATLAS), for the Chicago Area Transportation Study (Anas 1983b; Anas and Duann 1985), before he moved to Buffalo. The Urban Transportation Center of the University of Illinois in Chicago has become the location of Boyce's group specializing in models of location and travel, transportation network equilibrium and dynamic route guidance systems and in studies of parallel computing for urban and transportation modeling (Boyce 1990; Boyce, et al. 1992).

4 *Buffalo.* After his move to the State University of New York at Buffalo, Anas developed two microeconomic equilibrium models of urban housing markets, NYSIM, the New York Area Simulation Model, which is static and contains transportation (Anas 1992), and CPHMM, the Chicago Prototype Housing Market Model, which is dynamic and does not (Anas and Arnott 1991). Also in Buffalo, at the National

| | | |
|---|---|---|
| 1 | San Francisco | Landis, Prastacos |
| 2 | Urbana | Boyce, Kim, Rho |
| 3 | Chicago | Anas, Boyce |
| 4 | Buffalo | Anas, Batty |
| 5 | Cambridge, MA | Kain, Apgar |
| 6 | New York | Oppenheim |
| 7 | Philadelphia | Putman |
| 8 | Caracas | de la Barra |
| 9 | Santiago de Chile | Martinez |
| 10 | London | Mackett |
| 11 | Cambridge | Echenique, Williams |
| 12 | Stockholm | Lundqvist, Anderstig, Mattson |
| 13 | Dortmund | Wegener |
| 14 | Paris | Pumain |
| 15 | Turin | Bertuglia, Rabino |
| 16 | Seoul | Rho |
| 17 | Tokyo/Yokohama | Nakamura, Miyamoto |
| 18 | Nagoya/Gifu | Hayashi, Morisugi |
| 19 | Kyoto | Amano, Toda, Abe |
| 20 | Melbourne | Brotchie, Roy, Young |

**FIGURE 1: The map of active urban modeling centers.**

Center for Geographic Information and Analysis, Batty has resumed his former modeling work at Reading and Cardiff, United Kingdom, now for the Buffalo metropolitan area, in research on geographical information systems (Batty 1992).

5 *Cambridge, MA.* HUDS, the Harvard Urban Development Simulation (Kain and Apgar 1985) is a descendant of the NBER urban simulation model, the only model celebrated by Lee in his "Requiem." Completely reorganized by Kain and Apgar, HUDS was the first large-scale urban simulation model employing microsimulation techniques.

6 *New York.* Norbert Oppenheim of the City University of New York has produced several innovative extensions of logit-based equilibrium activity-allocation models (Oppenheim 1986; 1988; 1989).

7 *Philadelphia.* The modeling work of Putman (1983; 1991) is one of the few success stories of urban modeling. Originally developed at the University of Pennsylvania, it is now being performed by S. H. Putman Associates. Putman's recursive adaptation of the Lowry modeling framework ITLUP (Integrated Transportation and Land Use Package)

has been consistently refined over the last twenty years and, according to Putman, has been calibrated for nearly four dozen different urban/metropolitan regions in the United States and abroad, and used for more actual agency policy applications than any other spatial model.

8 *Caracas.* After earning his PhD with Marcial Echenique at Cambridge University, de la Barra established Caracas as the first center of urban modeling in Latin America. His TRANUS (Transporte y Uso del Suelo) model (de la Barra, et al. 1984; de la Barra 1989) has been applied for several Latin American cities, and for simulations of energy use and urban form with Rickaby of the Open University of Milton Keynes, United Kingdom (Rickaby 1991).

9 *Santiago de Chile.* Martinez (1991; 1992a; 1992b) is a new star on the urban modeling scene. He won the WCTR Conference Prize at the Sixth World Conference of Transport Research in Lyon in 1992 for his 5-Stage Land-Use Transport Model calibrated for Santiago de Chile.

10 *London.* Mackett at University College, London developed his Lowry-type LILT (Leeds Integrated Land-Use/Transport) model originally for the metropolitan area of Leeds (Mackett 1983), but later applied it to several British and foreign cities (Mackett 1990c; 1991a; 1991b), and developed an urban microsimulation model applied to Leeds (Mackett 1990a; 1990b).

11 *Cambridge.* The second success story of urban modeling is Echenique's MEPLAN, the latest in a sequence of increasingly versatile urban/regional models built on a generalization of multiregional input-output techniques (Echenique, et al. 1990; Hunt and Simmonds 1993). MEPLAN is being applied to more than a dozen urban regions in the world, including Greater London, by Echenique's Cambridge partnership and affiliate consultancies in Spain and Italy.

12 *Stockholm.* Stockholm has been a center of urban modeling through a unique constellation of people at the Royal Institute of Technology, the City of Stockholm and the Stockholm Regional Planning Office. Besides being the study area of the TRANSLOC (Transport and Location) modeling system and later developments (Lundqvist 1978; 1979; 1989) as well as more recent efforts (Anderstig and Mattson 1991), the city has been a test bed for several of the foreign models reviewed in this paper, such as those of Anas (Anas, et al. 1987), Boyce (Boyce and Lundqvist 1987), Kim and Rho (Lundqvist, et al. 1992) and Echenique.

13 *Dortmund.* At the Institute of Spatial Planning of the University of Dortmund (IRPUD), Wegener developed a model of urban housing and land markets, transportation and land use in the Dortmund region as part of a three-level hierarchy of spatial models (Wegener 1985; 1986a; Wegener, et al. 1991).

14 *Paris.* Pumain heads a group at the Institut National d'Études Démographiques which applies dynamic bifurcation models in the tradition of Allen (Allen and Sanglier 1981) to French cities (Pumain, et al. 1984).

15 *Turin.* Bertuglia made the Polytechnic of Turin a center of urban modeling and stimulated a number of model applications of Piedmont and Rome (Lombardo and Rabino 1984). In the late 1980s Bertuglia assembled an international group of scholars to outline a comprehensive dynamic urban model integrating both urban economics and spatial interaction modeling concepts (Bertuglia, et al. 1990), a grand design still waiting for implementation.

16 *Seoul.* After his work with Kim in Urbana-Champaign, Rho returned to Korea and established an urban modeling group at Hanyang University in Seoul.

17 *Tokyo/Yokohama.* The group of Nakamura at the University of Tokyo implemented the hierarchical Computer-Aided Land-Use Transport Analysis System (CALUTAS) for the Tokyo metropolitan area (Nakamura, et al. 1983). The group later spread to Yokohama, where Miyamoto independently developed the Random-Utility URBAN model (RURBAN), an equilibrium land market model (Miyamoto, et al. 1986, Miyamoto and Kitazume 1989).

18 *Nagoya/Gifu.* Hayashi, formerly in Nakamura's Tokyo group, continued work at Nagoya University with a land-use transportation model of Nagoya based on locational surplus (Hayashi and Doi 1989; 1992). Similar models, with a different concept of locational surplus, have been developed by Miyagi (1989) and Morisugi, et al. (1992) at Gifu University. Hayashi also developed a microsimulation model of residential mobility (Hayashi and Tomita 1989).

19 *Kyoto.* The group led by Amano at Kyoto University has been the origin of a major urban model implemented for Kyoto (Amano, et al. 1987; 1988) and of a model based on input-output techniques for the Kanto Region, by Ando (1991).

20 *Melbourne.* The Commonwealth Scientific and Industrial Research Organization (CSIRO) has produced the TOPAZ (Technique for Optimal Placement of Activities in Zones) optimization model for urban planning (Brotchie, et al. 1980) and a large volume of applied modeling work based on random utility (e.g., Roy 1992). Another Melbourne contribution is the land-use and transportation gaming simulation LAND developed by Young and colleagues at Monash University (Gu, et al. 1992).

Most of the above modelers know each other personally. Together they form an invisible college of remarkable coherence. Several of them were members of ISGLUTI, the International Study Group of Land Use Transport Interaction, which between 1980 and 1991 under the direction of Webster, Bly and Paulley of the United Kingdom Transport and Road Research Laboratory conducted the largest and most thorough comparative evaluation of large-scale urban models (Webster, et al. 1988; Webster and Paulley 1990; Webster and Dasgupta 1991). Today, the role of ISGLUTI has been taken over by the Special Interest Group "Land Use and Transport" of the World Conference on Transport Research, and by smaller, more informal associations in Europe and Japan. Urban modeling has a firm place at conferences of the Regional Science Association, the Association of Collegiate Schools of Planning (ACSP), the Association of European Schools of Planning (AESOP), or more recently at the International Conferences on Computers in Urban Planning and Management.

In addition, there has been a continuous debate about the purpose, direction and theoretical basis of urban modeling. It is worth remembering that some of the most influential theoretical contributions appeared after Lee's article or too shortly before it to be taken account of, for example, entropy-based spatial interaction (Wilson, 1967; 1970), random-utility choice (Domencich and McFadden 1975), bifurcation theory (Allen and Sanglier 1978/1979) and nonlinear optimization (Wilson, et al. 1981). The speed by which these developments were absorbed by the modeling community was documented in reviews by Harris (1985), Wegener (1986b; 1987), Kain (1987), Boyce (1988), Berechman and Small (1988) and Aoyama (1989) and in volumes edited by Hutchinson, et al. (1985) and Hutchinson and Batty (1986).

## Model Comparison

This section attempts to assess the current state of the art in urban modeling, taking account as much as possible of the criticism Lee put forth in the "Requiem." To do this, first a framework for the classification and evaluation of urban models is established. Then twelve contemporary operational urban models are evaluated, using as criteria comprehensiveness, overall structure, theoretical foundations, modeling techniques, dynamics, data requirements, calibration and validation, operationality, and actual and potential applications. It is shown that most of the criticisms of the *Requiem* have been taken account of by today's modelers or have been made redundant by advances in data availability and computing technology.

## A Model of Urban Models

For the evaluation of operational urban models, an idealized urban model will first be sketched out as a benchmark by which the existing models can be classified and evaluated. Eight types of major urban subsystem are distinguished. They are ordered by the speed by which they change, from slow to fast processes:

- *Slow change: networks, land use.* Urban networks such as transportation, communications and utility *networks* are the most permanent elements of the physical structure of cities. Large infrastructure projects require a decade or more, and once in place, they are continually updated and repaired but rarely abandoned. The *land use* distribution is equally stable; it changes only incrementally and is much more permanent than individual buildings.
- *Medium-speed changes: workplaces, housing.* Buildings have a lifespan of up to one hundred years and take several years from planning to completion. *Workplaces* (non-residential buildings) such as factories, warehouses, shopping centers or offices, theaters or universities exist much longer than the firms or institutions that occupy them, just as *housing* exists longer than the households that live in it.
- *Fast change: employment, population.* Firms are established or closed down, expanded or relocated in response to changing markets and technologies; this creates new jobs or makes workers redundant and so affects *employment.* Households are created, grow or decline and eventually are dissolved, and in each stage in their lifecycle adjust their housing consumption and location to their changing needs; this determines the distribution of *population.*
- *Immediate change: goods transport, travel.* The location of human activities in space gives rise to a demand for spatial interaction in the form of *goods transport* or *travel.* These interactions are the most volatile phenomena of spatial urban development; they adjust in minutes or hours to changing conditions such as congestion or fluctuations in demand.

There is a ninth subsystem, the *urban environment.* Its temporal behavior is more complex. The direct impacts of human activities such as transportation noise and air pollution are immediate; other effects such as water or soil contamination build up incrementally over time, and still others such as long-term climate effects are so slow that they are hardly observable.

Figure 2 illustrates the main interactions of the eight subsystems and their multiple links with the urban environment. It can be seen, for instance, that the location of workplaces, i.e. non-residential buildings such as factories, warehouses, office buildings and shops, depends on the location of other firms and of clients and workers, on access to goods transport and travel by customers and employees, and on the availability of land, utilities and housing. All eight subsystems are partly market-driven and partly subject to policy regulation.

## Twelve Urban Models

For the comparison, twelve models were selected from the work at the twenty modeling centers described above. The selection does not imply a judgment on the quality of the models, but was based simply on the availability of information. These are the twelve models:

- *POLIS:* the Projective Optimization Land Use Information System developed by Prastacos for the Association of Bay Area Governments (Prastacos 1986).
- *CUFM:* the California Urban Futures Model developed at the Institute of Urban and Regional Development of the University of California at Berkeley (Landis 1992; 1993).
- *BOYCE:* the combined models of location and travel choice developed by Boyce (Boyce, et al. 1983; 1985; Boyce 1986; Boyce, et al. 1992).
- *KIM:* the nonlinear version of the urban equilibrium model developed by Kim (1989) and Rho and Kim (1989).
- *ITLUP:* the Integrated Transportation and Land Use Package developed by Putman (1983; 1991).
- *HUDS:* the Harvard Urban Development Simulation developed by Kain and Apgar (1985).
- *TRANUS:* the transportation and land-use model developed by de la Barra (de la Barra, et al. 1984; de la Barra 1989).
- *5-LUT:* the 5-Stage Land-Use Transport Model developed by Martinez for Santiago de Chile (1991; 1992a; 1992b).
- *MEPLAN:* the integrated modeling package developed by Marcial Echenique & Partners (Echenique, et al. 1990; Hunt and Simmonds 1993).
- *LILT:* the Leeds Integrated Land-Use/Transport model developed by Mackett (1983; 1990c; 1991a; 1991b).

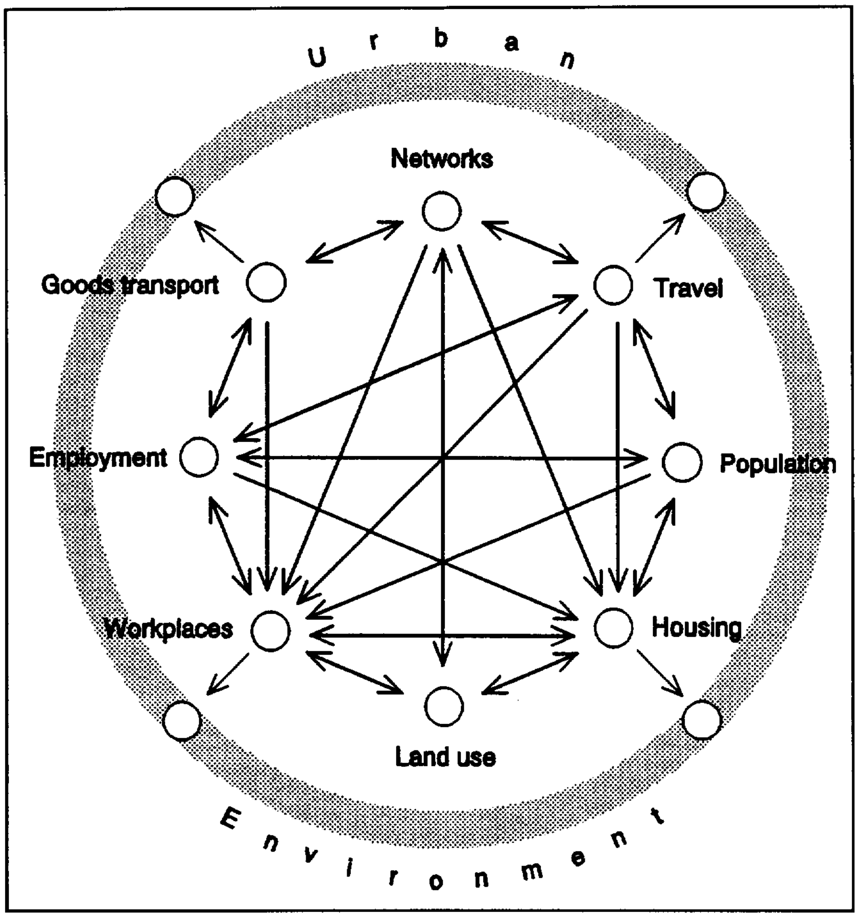


**FIGURE 2: A model of urban models.**

- *IRPUD:* the model of the Dortmund region developed by Wegener (1985; 1986a; Wegener, et al. 1991).
- *RURBAN:* the Random-Utility URBAN model developed by Miyamoto (Miyamoto, et al. 1986; Miyamoto and Kitazume 1989).

These twelve models will be classified according to the following criteria: comprehensiveness, overall structure, theoretical foundations, modeling techniques, dynamics, data requirements, calibration and validation, operationality, and actual and potential applications. Table 1 summarizes the comparison for the most important of these criteria.

### Comprehensiveness

All of the twelve models are comprehensive in the sense that they address at least two of the eight subsystems identified in Figure 2. However, it is ironic that twenty years after Lee, there are only two really comprehensive urban models, neither of which existed in 1973. Only TRANUS and MEPLAN encompass all of the eight subsystems of spatial urban development identified above. Both of these model residential and employment location, residential and non-residential floorspace supply and land consumption, and goods transport and travel, while taking account of network congestion.

All other models disregard one or another subsystem. LILT and IRPUD address all subsystems except goods transport, KIM models goods movements but not physical stock and land use, HUDS has a housing supply submodel but does not model non-residential buildings. Half of the models, in the tradition of the original Lowry model, make no distinction between activities (population and employment) and physical stock (housing and workplaces), and hence fail to model land use. Even more surprising is that of the twelve urban models, four (POLIS, CUFM, HUDS and RURBAN) do not consider transportation networks, i. e. fail to model transportation congestion endogenously. Only three models, HUDS, LILT and IRPUD, model demographic change and household formation.

### Model Structure

An important distinction between the models refers to overall model structure. Two groups can be distinguished. One group of models searches for a unifying principle for modeling and linking all subsystems; the others see the city as a hierarchical system of interconnected but structurally

**TABLE 1: Summary of comparison of twelve urban models**

| Model | Subsystems modeled | Model theory | Policies modeled |
|---|---|---|---|
| POLIS<br>*composite* | employment<br>population<br>housing<br>land use<br>travel | random utility<br>locational surplus | land-use regulations<br>transportation improvements |
| CUFM<br>*composite* | population<br>land use | location rule | land-use regulations<br>environmental policies<br>public facilities<br>transportation improvements |
| BOYCE<br>*unified* | employment<br>population<br>networks<br>travel | random utility<br>general equilibrium | transportation improvements |
| KIM<br>*unified* | employment<br>population<br>networks<br>goods transport<br>travel | random utility<br>bid-rent<br>general equilibrium<br>input-output | transportation improvements |
| ITLUP<br>*composite* | employment<br>population<br>land use<br>networks<br>travel | random utility<br>network equilibrium | land-use regulations<br>transportation improvements |
| HUDS<br>*composite* | employment<br>population<br>housing | bid-rent | housing programs |
| TRANUS<br>*composite* | all subsystems | random utility<br>bid-rent<br>network equilibrium<br>land-use equilibrium | land-use regulations<br>transportation improvements<br>transportation-cost changes |
| 5-LUT<br>*unified* | population<br>networks<br>housing | random utility<br>bid-rent<br>general equilibrium | transportation improvements |
| LILT<br>*composite* | all subsystems<br>except goods<br>transport | random utility<br>network equilibrium<br>land-use equilibrium | land-use regulations<br>transportation improvements<br>travel-cost changes |
| MEPLAN<br>*composite* | all subsystems | random utility<br>network equilibrium<br>land-use equilibrium | land-use regulations<br>transportation improvements<br>transportation-cost changes |
| IRPUD<br>*composite* | all subsystems<br>except goods<br>transport | random utility<br>network equilibrium<br>land-use equilibrium | land-use regulations<br>housing programs<br>transportation improvements<br>travel-cost changes |
| RURBAN<br>*unified* | employment<br>population<br>housing<br>land use | random utility<br>bid-rent<br>general equilibrium | land-use regulations<br>transportation improvements |

autonomous subsystems. The resulting model structure either is tightly integrated, "all of one kind," or consists of loosely coupled submodels, each of which has its own independent internal structure. The former type of model is called "unified," the latter type "composite" (Wegener, et al. 1986). Of the twelve sample models, four (BOYCE, KIM, 5-LUT and RURBAN) belong to the unified category, and the remaining eight are composite. The distinction between unified and composite model designs has important implications for the modeling techniques applied and for the dynamic behavior of the model. (See below.)

**Theory**

Nowhere is the difference between the modeling scene Lee critiqued and present models greater than in the area of theory. Lee was right in criticising the poor theoretical foundations of the urban models of his time. In the meantime, however, great advances with respect to appropriate theories for explaining spatial choice behavior and in empirical techniques for calibrating spatial choice models have been made. This has led to a broad consensus about what constitutes a state-of-the-art urban model.

Except for one (CUFM), all models in some way or other rely on random utility or discrete choice theory to explain and forecast the behavior of urban actors such as investors, households, firms or travelers. Random utility models predict choices between alternatives as a function of attributes of the alternatives, subject to stochastic dispersion constraints that take account of unobserved attributes of the alternatives, differences in taste between the decision makers, or uncertainty or lack of information (Domencich and McFadden 1975). Anas (1983a) showed that the multinomial logit model resulting from random utility maximization is, at equal levels of aggregation, formally equivalent to the entropy-maximizing model proposed by Wilson (1967; 1970); he thus laid the foundation for the convergence and general acceptability of formerly separate strands of theory.

Underneath that uniformity, however, there are significant differences between the theoretical foundations of the models. Probably the most important difference is the degree to which the models treat the urban system as a system of markets. Half of the models (KIM, HUDS, TRANUS, 5-LUT, MEPLAN, RURBAN) model the land (or floorspace or housing) market with endogenous prices and market clearing in each period; one (IRPUD) has endogenous land and housing prices with delayed price adjustment. These models are indebted to microeconomic theory, in particular to Alonso's (1964) theory of urban land markets or bid-rent theory. The six models without market equilibrium rely on random utility maximization; however, two of the microeconomic models (5-LUT and RURBAN) are hybrids between bid-rent and random utility theory. All models with transportation submodels use random utility or entropy theory for modeling destination and mode choice.

Only KIM determines a general equilibrium between transportation and location in the strict economic sense of equilibrium between supply and demand with endogenous prices. The other models are equilibrium models of transportation only (ITLUP, IRPUD), of transportation and activity location linked by delays (TRANUS, MEPLAN), or of transportation and location combined, but without endogenous prices (BOYCE, LILT). The activity-location models of POLIS, CUFM, ITLUP and IRPUD are not equilibrium models, but apply various concepts of locational surplus (POLIS), random utility (ITLUP, IRPUD) or profitability (CUFM) to locate activities. ITLUP may be brought to general equilibrium, but this is not normally done.

Besides these dominant theoretical foundations, several other theoretical elements are built into some models. TRANUS and MEPLAN use export base theory to link population and non-basic employment to exogenous forecasts of export industries. HUDS, LILT and IRPUD apply standard probabilistic concepts of cohort survival analysis in their demographic and household formation submodels. IRPUD also utilizes ideas from time geography, such as time and money budgets, to determine action spaces of travelers in its transportation submodel.

**Modeling Techniques**

In all twelve models, the urban region is represented as a set of discrete subareas or zones. The temporal dimension is represented by subdividing time into discrete periods of between one and five years. This classifies them as recursive simulation models.

However, beyond this commonality is a great variety of modeling techniques. One area of variation is how the equilibrium between transportation and location in equilibrium models is found. Here the distinction between unified and composite models comes into play. Obviously, optimization techniques can be applied only within one submodel or where the whole model is "all of one kind." In this respect the unified models (BOYCE, KIM, 5-LUT and RURBAN) shine. In six of the twelve models (BOYCE, KIM, TRANUS, LILT, MEPLAN, RURBAN), transportation and location are simultaneously determined in spatial-interaction location models, in which activities are implicitly located as destinations of trips; in the remaining six models transportation influences location via accessibility indicators. In the eight models with network representation (all except POLIS, CUFM, HUDS and RURBAN), state-of-the-art modeling techniques with multi-modal network representations are applied, with network equilibrium the dominant trip assignment method despite its well-known weakness of collapsing to all-or-nothing assignment in the absence of congestion. Only ITLUP, TRANUS and MEPLAN have a multiple-path assignment allowing for true route-choice dispersion.

For representing intraregional flows of goods, multiregional input-output methods are the standard method. KIM, TRANUS and MEPLAN use input-output coefficients or demand functions for determining intersectoral flows, and random utility or entropy models for their spatial distribution. TRANUS and MEPLAN have generalized this to incorporate industries and households as consuming and producing "factors" giving rise to goods movements or travel.

With the exception of CUFM and HUDS, all models are aggregate in their input and output at a meso level, i. e. all results are given for medium-sized zones and for aggregates of households and industries. CUFM and HUDS are entirely disaggregate, i. e. they apply microsimulation techniques to disaggregate input data. HUDS works on a sample of disaggregate data of individual households in list form, whereas CUFM uses detailed land information in map form generated by a geographical information system. IRPUD is peculiar in that it starts with aggregate data but uses microsimulation techniques with endogenous sampling in its housing market submodel.

### Dynamics

Recursive simulation models are called quasi-dynamic because, although they model the development of a city over time, within one simulation period they are in fact cross-sectional. This is however only true for strictly unified models. Composite models consist of several interlinked submodels that are processed sequentially or iteratively once or several times during a simulation period. This makes composite models especially suited for taking account of time lags or delays due to the complex superposition of slow and fast processes of urban development (cf. Wegener, et al. 1986). However, this feature is insufficiently used by the models, because the typical period of five years has already the effect of an implicit time lag—a too-long time lag in most cases.

### Data Requirements

It was one of Lee's major complaints against large-scale urban models that they were "data-hungry." This is partly still true today. The data collection for a model of a large metropolis has remained a major effort. However, in many cases the introduction of computers in local government has generated a pool of routinely collected and updated data that can be used as the information base for a model, in particular in the fields of population, housing, land use and transportation.

Another factor likely to reduce the data-dependency of urban models is the significant progress made in urban theory in the last decades. In general, the models of today are more parsimonious, i. e. can do with less data than their predecessors did twenty years ago. Examples illustrating this are the techniques to generate regional input-output matrices from national input-output matrices and regional totals through biproportional scaling methods; or techniques to create artificial microdata as samples from multivariate aggregate data.

### Calibration and Validation

Lee claimed that it was one of the fundamental flaws of large-scale models that there did not exist reliable and efficient techniques for calibrating their parameters, i. e. determining those values of the parameters of their equations that yielded the best correspondence of the model results with observations from reality.

The twelve models of the sample demonstrate that such methods now exist. All of them have been (or could have been) estimated from observed data, using readily available computer programs and following well-established methods and standards. In particular, maximum-likelihood estimation of the ubiquitous logit model has become a routine activity.

Nevertheless, in one respect Lee's criticism is as valid today as it was twenty years ago. While calibration has become easier, the limits to calibrating a model with data of the past have become visible. Calibration of cross-sectional models, as it is practised today, provides the illusion of precision, but does little to establish the credibility of models designed to look into the far future. There has been almost no progress, moreover, in the methodology required to calibrate dynamic or quasi-dynamic models.

In the face of this dilemma, the insistence of the authors of some models in the sample on "estimating" every model equation appears almost an obsession. It would probably be more effective to concentrate instead on model *validation*, i. e. the comparison of model results with observed data over a longer period. However, remarkably few validation exercises are reported in the modeling literature—even the ISGLUTI report (Webster, et al. 1988) deals rather cursorily with validation issues. In the future, the only real test of a model's performance should be its ability to forecast the essential dynamics of the modeled system over a past period at least as long as the forecasting period. There are only two models in the sample following this philosophy, MEPLAN and IRPUD. These models are partly calibrated not by statistical estimation techniques, but by manual fine-tuning in a long, interactive process.

### Operationality

All the models in the sample are operational in the sense that they have been applied to real cities, but they are operational to different degrees. Some of them still fit Lee's description of poorly documented monster programs executed on mainframe computers and understood only by their authors. At the other end of the spectrum are the few models that are on their way to become standard software for a wider market. Among these, TRANUS stands out as a particularly advanced and well documented software running under Windows 3.1, with an attractive user interface in Spanish or English. The time seems not far when any planning office will be able to buy a complex and versatile urban model with full documentation, default values and test data sets for less than a thousand dollars.

Not all models have progressed in that direction as far as TRANUS has. The majority of them operate in a middle ground between the two extremes. Many model programs are currently being ported from mainframe to workstation or PC platforms, with the distinction between the two more and more blurred. These models benefit from the vast increase in memory and computing speed and the associated gain in autonomy, convenience and graphical capabilities offered by small computers. However, there is also an opposite movement. Some modelers explore the potential for solving hitherto intractable computing tasks by turning to the fastest super computers available (BOYCE, KIM).

### Actual and Potential Applications

If one considers the enormous range of planning problems facing a typical metropolitan area in industrialized countries today, the spectrum of problems actually addressed with the twelve urban models in the sample is very narrow. The majority of applications answer traditional questions such as how land use regulations or housing programs would affect land use development and transportation, or how transportation improvements or changes in travel costs would shift the distribution of activities in an urban area.

These are and will continue to be important questions—questions that can only be answered with the kind of models discussed here. However, other issues are likely to become prominent in the future, and it will be essential that urban models be able to make a significant contribution to their rational discussion. Issues that seem to deserve more attention by urban modelers are equity and environmental issues. To forecast the distributional effects of policy measures in the fields of employment, housing or transportation is well within the range of what the models can do if they are made more sensitive to these dimensions. ITLUP and MEPLAN contain evaluation modules calculating consumer surplus indicators for various groups. Environmental applications are gaining in importance, as simulations of the energy consumption of transportation by models such as TRANUS and IRPUD demonstrate. Other applications addressing ecological issues such as noise propagation or air pollution are in easy reach and are likely to become standard features of advanced urban models in the future.

New legislation inspired by growing environmental awareness may accelerate the greening of urban models. In the United States the Intermodal Surface Transportation Efficiency Act of 1991 requires that new transport projects in non-attainment areas must demonstrate that they do not have negative impacts on air quality, and the amended Clean Air Act of 1990 demands that air quality forecasting must consider the interaction between transportation and land use in a consistent fashion—as can be done only by land-use transport models. ITLUP's link to the air quality model of the Environmental Protection Agency may herald a new era of urban models used for environmental analysis.

## Conclusion

A brief paper like this is much too short to convey an impression of the immense achievement and richness of approaches in urban modeling during the last two decades. In particular, because of the paper's focus on *operational* urban models, it could not do equal justice to the parallel development of *theoretical* urban models. However, there has been a constant flow of ideas and innovations from theoretical to applied modeling work in the past, and it can be expected that the theoretical field will continue to influence the state of the art of operational urban models in the future. Moreover, there exist at this very time exciting opportunities to incorporate new theoretical developments and methodologies into the field.

Several avenues seem promising. The likely further increase in memory and speed of small computers will continue to lower the barriers to making urban models a routine tool for the exploration of urban futures by a widening range of institutions and individuals, including non-experts. However, this tendency must be supported by the development of attractive and efficient user interfaces for interactive manipulation of inputs and inspection of results. The Windows-based user shell of TRANUS, Young's gaming simulation LAND (Gu, et al. 1992) and Batty's model visualization system (Batty 1992) are leading the way in this direction.

On the other end of the computing spectrum, the usefulness of super computers for urban modeling has yet to be ascertained. The question seems to depend very much on whether equilibrium models requiring nonlinear programming solutions will continue to be a main target (cf. Harris 1993). Boyce (1988) and Kim (1989) argue that new, formerly intractable tasks such as network design problems formulated as bilevel programming models may pose new magnitudes of computing needs and hence require super computer capabilities. However, study is needed of whether the added complexity imposed by parallel computing would impose more restrictive constraints on problem formulation than the added speed is worth. Lastly, the speed on a remote super computer should be weighed against the convenience and flexibility of slower but autonomous local computing; the ultimate solution to this conflict may be the desktop super computer.

Other methodological innovations of potential benefit to urban models are related to developments in the field of geographical information systems (GIS). Despite their recent popularity, GIS have so far contributed surprisingly little to methodological innovation in urban analysis. The theoretical vacuousness of GIS can be remedied only if they are linked to the analytical capabilities of urban models. However, the world of GIS and the urban modeling world are still far from each other. It would be a challenge to explore what forms of analytical models are appropriate for the data structures provided in GIS. One conjecture is that microsimulation may have a certain affinity to the way spatially disaggregate microdata are stored as point coverages in GIS. This might provide additional impetus to recent experiments with microsimulation models of spatial behavior going beyond the rule-based activity location in CUFM (Hayashi and Tomita 1989; Mackett 1990a; 1990b)

Also of potential interest are knowledge-based or expert systems. Like GIS, knowledge-based systems have so far been applied mostly to tasks of little interest to urban modelers. However, this need not be so in the future. Heikkila, et al. (1989) report on an interesting project in which an expert system, a GIS and an instantiation of Putman's ITLUP were coupled to form a decision support system for infrastructure improvements.

The greatest challenge, however, seems to be to open up urban modeling to new problem fields. As has been demonstrated, urban models have in the past been applied mainly to a very narrow set of planning problems, and have failed to adapt to changing perceptions of problems. In particular, models should be made more sensitive to issues of equity and of environmental sustainability. Only if the models prove that they are able to give meaningful answers to the urgent questions facing cities on these matters can they establish for themselves a firm position in the planning process of the future.

Some may find it ironic that it requires the urgency of the environmental debate to grant urban models a new lease of life. It is indeed puzzling to see that even vigorous critics of "rational" models in planning call for just that kind of method for tackling environmental problems. However, the new respect for models is more than just another twist in the intellectual debate about rationality in societal planning. It heralds the twilight of postmodernity in the face of growing risks of ecological disaster. Urban models have a renewed chance because they stand for rationality, and rationality is again needed.

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