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Modelling Land Use and Transportation Dynamics: Methodological Issues, State-of-Art, and Applications in Developing Countries

Harry Timmermans

Urban Planning Group, Eindhoven University of Technology
Vertigo 8.18, PO Box 513, 5600 MB Eindhoven, The Netherlands
Email: H.J.P.Timmermans@tue.nl

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Introduction

The distribution of land use and transportation are strongly connected. Land use configurations influence the generation and attraction of transport flows. Vice versa, the location of firms and to some extent households may be influenced by accessibility and other feature of the transportations system. Changes in one component will influence the dynamics of the other.

It is not surprising therefore that transportation engineers and urban planners alike have developed their models of urban and transportation dynamics. Although their models share some common concepts, there are also differences in flavour and sometimes contents, which can be largely explained by the difference in focus and responsibility of the two professions. Integrated land use-transportation models have been primarily developed by transportation engineers. These models often have much detail in the simulation and prediction of the transport system component. Land use is either exogenously given or sometimes explicitly models typically using simplified or perhaps even simplistic versions of more dedicated dynamics developed in urban planning, regional science and related disciplines. In contrast, the focus of models developed in these disciplines is often on dynamics in land use, either leaving out the transportation system virtually altogether or incorporating it in a reduced manner.

The application of such models requires a substantial amount of data that also need to be maintained. It is therefore not surprising that most applications of these models can be found in developed countries with access to a lot of data. The evolution of these models evidences a tendency of increased complexity, which in turn involves higher data demands. The question then becomes whether such complex models can also be applied in developing countries where often such data are not available.

In light of these considerations, this paper addresses two related issues. First, it briefly discusses some developments in modeling urban and transportation dynamics and identifies some challenges and prospects. Secondly, the implications of these developments for the application of these models in developing countries are discussed. The paper will concentrate on integrated land use –transportation models, mainly developed in transportation research and on cellular automate models, mainly developed in urban planning.

Cellular automata models

Cities are rarely in equilibrium, almost all cities are undergoing continuous growth, change, decline and restructuring – usually simultaneously. This very nature of cities makes it unrealistic to study them in terms of concepts that are derived from stable equilibrium states. Cellular Automata (CA) models have been suggested as an alternative to examine urban land use dynamics.

The theoretical underpinnings of a CA model are quite simple: space is divided into an array of cells. Each cell represents a particular type of land use. A series of transition rules is formulated and enforced to govern transitions between land uses, typically as a function of the states of a configuration of adjacent cells. The successive application of these rules then results in possible land use changes, describing the evolution of the system. These principles imply that every student with just a modest training can develop a CA model in just a couple of hours. It is not surprising that they have been used as pedagogical tools a lot.

CA models have two characteristics that make them inherently attractive for application to geographical problems. The first is that they are in itself spatial, and the second is that they can generate very complex forms by means of very simple rules. Generally they operate in a self-organizing way that evolves through rules and constraints.
CA models were originally developed by the physicist Ulman in the 1940s and were used by von Neumann to investigate the logical nature of self-reproducing systems. Research on CA has grown rapidly since Wolfram showed that these apparently simple systems can generate very complex structures, and demonstrated that they therefore provide a useful technique for exploring a wide range of fundamental theoretical issues in dynamic and evolution (White and Engelen 1993). Currently, CA models are being used by researchers from a variety of disciplines to investigate questions concerning the origin and evolution of structure.

The definition of the “CA neighborhood”, one of the fundamental aspects of the CA, has changed with the development of the models. The question concerning the dimension of the neighborhood drew the attention of those dealing and developing CA models, and various formulations of the neighborhood were proposed. Von Neumann originally defined the neighborhood of a cell as the 4 adjacent cells (North, South, East, and West) of the cell. Moore added another 4 cells for the neighborhood definition: the NW, NE, SE and SW cells, adjacent to the cell of interest. Couclelis (1985) defined the size of the neighborhood differently for each land use. White and Engelen (1993) defined the neighborhood of a cell to be cells within a radius of 6 cells, so that according to this definition the neighborhood contains 113 cells. However, the influence of the neighborhood may also be given a weight of zero, which makes the effective neighborhood smaller. According to Semboloni (1997) a cell is dependent on the immediate neighborhood, which includes eight surrounding cells. The different definitions typically reflect different assumptions about the spatial process under investigation.

Over the years, several cellular automata models of land use change, which attempt to shed light on urban planning aspects, have been suggested in the literature. Tobler (1979) was perhaps the first to recognize the advantages of cellular models. Couclelis (1985, 1988, and 1989) elaborated the approach and examined the possible uses of cellular automata models in the context of urban planning. Couclelis’ models were not intended to be a realistic representation of urban processes. They were used primarily as aides in theoretical experiments, and with the help of these models she provided important insights into the nature of geographical processes. First, she developed a basic game of life. This was done while trying to overcome some of its problems: the ability to define different shapes and sizes of neighborhoods for different cells, the restriction of regular grid patterns and the informality assumption according to which, every cell is exactly the same as any other cell. Based on Couclelis’ basic research it was concluded that the regularity assumption of the model makes it almost impossible to apply the cell-space idea to real world areas containing zones with irregular boundaries and varying number of neighbors. In addition, these studies mention the limitation of space and time invariant transition rules and the closure of the system to external events. As was described, local laws (for a specific cell) are problematic as it precludes any consideration of global (city scale) factors such as site accessibility, attractiveness relative to other sites across the city, market conditions of supply and demand, and so on. In a later model, Couclelis included different values of states for different cells, different influencing neighbors and a global transition function that link local interactions and global states. Based on that model, space no longer needs to be homogeneous either in the properties or in its structure. Neighborhoods need not to be uniform across space. Now, although one may argue that by allowing for such variation, strictly speaking we are no longer talking about cellular automata models, this flexibility in assumptions have been accepted by the research community, primarily because the grid structure and the set of transition rules constitute a simple simulation platform. Consequently, many operational cellular automata models have been developed.

Itami (1994), for example, described an effort to enhance an existing GIS in a program called SAGE to facilitate the use of CA, in order to simulate population dynamics. He extended the neighborhood from the 3-5 cells- linear neighborhood, to a 9 cell square neighborhood (the cell and 8 nearest neighbors). Two models were described. In the first one, the rules are implemented without environmental constraints. In the second model, environmental constraints were added, to demonstrate in a simple way, how environmental factors might be incorporated into a CA model. Itami concluded that although SAGE is not fully developed it is clear that CA
theory presents a great challenge and opportunity for environmental planning. The model limitations include the assumption that the higher level of macro level phenomena arise entirely from the interactions between certain kinds of micro-components of lower levels, and the assumption that all the cells must scan the environment and act at the same instant in time.

Related to the latter issue, Batty and Xie (1994) illustrated the power of CA for urban simulations by developing a non-deterministic CA model—which computes birth and death amongst the configuration of active cells at time “t” stochastically. The neighborhood has a threefold hierarchy: immediate neighborhood, interaction field and a wider region. In the model only two states exist: developed or undeveloped. They illustrated some primary insights into the pattern of urban development, which results from the repeated operation of local simulation rules. The emphasis in another publication (Batty and Xie, 1997) is not just upon possible model structures, but also upon possible urban forms, which such structures are able to generate. They defined a different neighborhood for each activity and the transition functions need not to be universal. Thus, a specific neighborhood was defined for each one of the four land-uses included in the model. After running the model they concluded that many variants of these processes can exist but what is clear is that CA models provide an effective basis for simulating realistic patterns which reflect reasonable rules for the way cities develop. As they claim, it is unlikely that current approaches can really generate acceptable levels of performance in terms of fit to existing patterns, and thus the emphasis in applications should not be on fit but on feasibility and plausibility. However, developing models for actual reality as well as virtual reality is an important idea in advancing these approaches, which in the final analysis must be applicable to contemporary urban problems.

Cecchini (1996) developed also a non-deterministic CA model (NDCA). The basic assumption of this research is that even if we had a flat and uniform piece of land in the strictly physical sense, production, consumption, capital, population and other elements would not spread in contiguous and uniform patterns on the whole land. According to Cecchini, it is not always necessary to take the Neighborhood State as the input, rather, it is sometimes sufficient to control the internal state of the cell and to define non-deterministic transition rule leading to an expected state. At other times, Cecchini suggests that it is possible to avoid dealing with all-cell analysis and to base the evaluation of the system only on the random choice of cells. The first model developed by Cecchini was the FicTies (fiction cities). Based on this model, Cecchini developed a few more models, one of which is the AUGE model. The latter provides a generic modeling framework which enables users to: (1) define characteristics of cellular space; (2) define transition rules; (3) formulate a library of events for studying the transition of general models into local formulations; and (4) use real maps and data.

Cecchini and Viola (1990, 1992) also used CA to model the urban growth process. They view the city as a continuously evolving object whose complex, large-scale structure is the commutative results of the local application of relatively simple decision rules. Phipps (1989) used constrained automata with stochastic disturbance of the cell states to investigate certain basic principles of spatial structuring. Frankhauser (1991) showed that a cellular model of tumor growth could also be interpreted to represent the growth of an urban area. Hillier and Hansen (1984) developed a cellular approach to the generation of spatial structure, which they used successfully to model and explain both the built form of a French village and the layout of rooms in houses.

White and Engelen (1993) developed a model that aimed at investigating basic questions of urban form that was kept as simple as possible. In contrast to the above studies they applied a fractal kind of approach, and concluded that the specific urban form is very sensitive to random changes and initial conditions. The constraints imposed by the initial configuration can override the stochastic effect. They compared the development of real cities and the result of the CA. This comparison showed that the model appears to capture some of the key features of urban structure in a relatively realistic way. In this model there are four types of land-use: vacant, housing, commercial and industry. The neighborhood of the cell consists of 113 cells, including the possibility of giving a value of zero to the most distant cells. This study determined a
hierarchy of land-use states such that a cell may only be transformed from a lower to a higher state, that is, the city could only grow when non-occupied cells could be converted to vacant ones, which was determined to be the lower level. In later studies this restriction was relaxed. In each iteration, the transition potential is calculated for all allowed transitions and sufficient cells are converted to each land-use. The cells that are converted to each state are those with the highest potential for that state. White and Engelen claimed that one of the limitations of the model, as of the previous models, is the size of the cell, as each cell has only one land use. This problem gets bigger as the size of the cell makes it impossible to show many city elements such as for example kindergartens, schools and neighborhood parks.

In another publication, White and Engelen (1997) developed a model that aimed to achieve some understanding of how useful CA might be in forecasting and planning applications. At each iteration, for each cell not occupied by a fixed state (cells that are used to represent features that are considered to be permanent such as rivers, parks and railways), a set of transition potentials is calculated, including the state of the cell is already in. These transition potentials reflect the intrinsic suitability of the cell for each active land use and the aggregate effect of the various land uses within a neighborhood of the cell, some land uses are incompatible as neighborhood, others are mutually reinforcing. The level of demand for cells in the various activity states is provided by the macro-scale model for regional dynamics, which consist of three linked models: (1) a model of the natural environment; (2) a demographic model; (3) an economic model. This macro model determines some cell state changes and the demand for change in cell states. The neighborhood is again 113 cells. The transition potentials also take into account the inherent suitability of the cell itself, and the effect of the stochastic perturbation. Once the transition potential is calculated, each cell is converted to the state for which it has the highest potential. However, this process is subjected to important constraints, in which the number of cells in each iteration is not left to be determined incidentally by the application of the state of the transition rules. Because the growth of a city depends essentially on its position in a larger urban-economic system, in this model there is the constraint that the total number of cells in each state is equal to totals supplied exogenously at each iteration. This is achieved by converting each cell to the state for which its potential is highest but only until the required number of cells for a given state is attained. Once that point is reached, the potential of all other cells for that state is set to zero. In order to examine the role of the suitability and the transport network in determining the urban form, several simulations were performed in which these factors were manipulated. These simulation results suggested that the transportation network is a primary determinant of the visual urban form and the suitability is the secondary influence on the pattern of the city.

In another paper, White et al., (1997) examined the CA model in the context of a generalized application to the city of Cincinnati Ohio. First, a pilot project application was developed, with a calibration to the city, and then various sensitivity experiments were conducted to examine how it behaves under the circumstances. This study was based on land-use data from 1960. The varieties of land uses were collapsed into three active categories: commerce, industry and housing. For the industry, the study included a suitability map. They found the simulation results “look like” Cincinnati. In order to examine a little more closely the role of the suitability and the transport network in determining the urban form, several simulations were performed in which these factors were manipulated. They concluded that in spite of the inherent stochastic nature of the system it is possible to make relatively reliable predictions of urban land use patterns.

Wu and Webster (1998) further explored possible ways to obtain a more realistic description, and thus dealt with the question of how to define microscopic transition rules in a more realistic way. This was done while taking into account that the transition of non-urban space into cities depends on global as well as local processes. Such an approach is important to create a realistic model and results. This study included a Multi-criteria Evaluation (MCE)- CA framework, which allows a multi-use gaming scenario in which different users evaluate a region and compete against each other. Their models allow entering preferences of developers for land at a
specific location. The purpose of using the MCE is to explore more systematically how factor weights contribute to the outcome. The emphasis is on providing a mechanism by which the generic results of alternative development regimes may be explored. In this model there are only two states: vacant and urban. Similar to White and Engelen (1993) it is possible to change only from vacant to urban and not the other way around. As there are no different urban land uses there are no competing elements in their transition rules. In this study, they aimed at understanding the huge process of expansion of Guangzhou, the largest city in Southern China. Four different scenarios were checked, (For example, a center dominant growth- emphasizes the role of the city center, compared with giving a higher preference to access to the major industrial district), which gave different goodness of fit results when comparing to the real city. In their conclusion, first they noted that CA is not well suited for the prediction of land use of individual sites. They assume the city to be at least, in part a self-organizing system, in which case the use of particular sites is unpredictable. They predict the shape of the total system and probabilistic transition rules and concluded as other previous researchers, that it is unlikely that behavior governing past phases of development will hold exactly for future phases; more important are the attitudes of different actors in the development process towards the future. The MCE was certainly found in that study to be a good approach for capturing preferences to govern a CA simulation.

Ward et al., (2000), based on previous results, emphasize the need to include global patterns when developing the urban area. They argued there is a need to consider urban development as a process that is self-organizing at the local level but that is constrained and modified by broad-scale factors. To incorporate global factors in CA models, transition rules must reflect significant factors that influence urban development as a range of socio-economic and biophysical factors. The orientation of models developed in this study, is toward the application of regional-scale growth scenarios. For example, given a population projection and land use constraints, what is a possible pattern of future growth, so that, in this case models that produce regional-scale urban morphologies are adequate without the need to pursue detailed urban morphology at local level? In the model developed three constraints were defined: land slope, distance from roads and distance from population centers. A probabilistic model was developed including the three constrains. The model described in their research dealt with residential growth only, but they model can be extended to a multi-state model that includes a number of different urban land uses.

A step forward in including some global effects in the CA model was made in a study of Wu and Martin (2002), who incorporated the regional population projection into the simulation. In this study, they described a CA simulation of urban expansion (in southern England). The main objective of this paper is to explore the use of CA in applied contexts. They suggest that CA simulation is useful in exploring future urban growth by understanding the impact of different development conditions. This extends classical CA built upon abstract rule definition to hybrid CA based on detailed real-world data and constraints. An accessibility surface was included, dealing with train and travel distances to road junction and to the nearest settlement with population of over 10,000 population. A complete set of motorway-access points has been digitized, and distances calculation to each cell. The base for the data included in a census (a postcode system).

Yeh and Li (2001) developed a CA model, which included the new concept of “Grey-cell”. They claimed that the fact that in each iteration of the CA model a cell is selected or not for conversion (development) is not a realistic situation. In reality, usually a cell is not ‘suddenly’ mature for development. It is more realistic to select a cell for conversation gradually through a couple of iterations based on commutative process. A “Grey cell” can be defined to address the state of this continuous selection. The state of a cell in a “Grey-cell” method us expressed by a *continuous value for development or conversion. The value indicates the cumulative degree of development for a candidate cell before it is completely selected for development or conversion. (For example values between 0-1, while a cell is not regarded as a developed cell until the value reaches 1). In addition, the model developed contains local, regional and global constraints. The
local constraints are: amount of developed cells, agricultural suitability and radius for the nearest sub-center. The regional constrains are: distance from center and distances from protected sources as drinking water, forest and wetland. For the global constrains density control was used. The factors in the model developed are mainly generic. The model was run several times including the listed constraints and the “Grey-cell” concept. In each iteration, constraints were emphasis so that different city scenarios were generated. They concluded that planners and government officials could use the “Grey-cell” constrained CA model as a planning support system to formulate strategic urban development plans to meet the objectives of sustainable development.

As we have argued, a limitation of cellular automate models is that cells are no decision makers. An interesting approach therefore was explored by Ligtenberg et al. (2001), who combined CA and the MAS (Multi-agent simulation) technique to build a spatial multi-actor model that simulates spatial change as a result of actor-based decision-making. Their definition of an agent is “a system that tries to fulfill a set of goals in a complex, dynamic environment. An agent is situated in the environment: it can sense the environment throughout its sensors and act upon the environment using its actors”. To illustrate this integration, a land use simulation model was presented which included one type of land use-urbanization. The model mimics a number of actors who by negotiation allocate new locations for urbanization. To do so, each actor develops a series of preferences through time that design its ideas about a future organization of the environment. These preferences of the individual actors are translated into a new land use configuration through a process of voting and decision making on possible allocations. In the current model there are two types of actors. The first is the reconnaissance, which only allowed communicating an opinion about a future land use situation, the second agent is the planning actor that has also the authority to change the spatial organization. Their decisions are based upon the opinion of the other actor and upon his ideas. This typology mimics the situation in which various actors participate in land use planning, leaving the actual authorization to change to a selected group of actors. A pilot application was developed for the eastern part of the Netherlands. Three agents were implemented, they were called “Municipality of Nijmegen”, “the new rich” and “nature of environment”. So that, this model included agents that are policy makers and not the inside actors which are the residents (people and organizations). The municipality has been assigned the status of planning actor. This approach was found to be a useful tool for planning.

This limited, but representative, literature review clearly shows the development of the CA model over the last three decades. Originally, inspired by complexity theory, the models were developed to demonstrate that simple rules could induce complex dynamics and generate emerging patterns. Such “games” serve educational purposes and theoretical explorations very well. Over the years, however, cellular automata models have also been developed as decision-support system that would help planners to gain more insights into the likely consequences of their decisions or even as models that predict urban evolution. In that sense, cellular automata model are direct competitors of integrated transport land use models that we will discuss later on. To make cellular automata appropriate for such planning applications, some key characteristics have been elaborated. The examples discussed above emphasize the inclusion of various constraints at various levels, the variable timing of events and different definitions of the neighborhood. Other progress includes studies about the impact of border conditions, calibration algorithms, improved goodness-of-fit functions, the impact of spatial resolution, to name a few. Although these research efforts have increased our body of knowledge, the application of cellular automata models is fundamentally limited by the fact that the approach does not model human decision-making that ultimate determine changing land use patterns. The focus of the approach is on outcomes of such complex process and not on the processes themselves. This implies that the value of the models depends on the temporal stability of the observed outcomes and their underlying dynamics as captured in the transition rules. Even if this would be sufficient and assuming that the models successfully represent the influence of a set of factors on the transitions, the value of cellular automata models to planning practice is
still limited as these models do not have any mechanisms to predict how stakeholders react to new policies or to emerging phenomenon for the system at large. Cells are no decision-making units. Cellular automata do not contain any principles of individual decision making.

**Integrated land use – transport models**

Integrated land use transportation models represent attempts of predicting future land use change and transportation patterns simultaneously. One of the first models in this tradition was developed by Lowry (1963, 1964) for the Pittsburgh urban region. He distinguished population, service employment and basic (manufacturing and primary) employment, and these activities correspond to residential, service and industrial land uses. Activities are translated into appropriate land uses by means of land-use/ activity ratios. The division of employment into service and basic sectors reflects the use of the economic base method to generate service employment and population from basic employment. The model allocates these activities to zones according to the potentials of zones. Population is allocated in proportion to the population potential of each zone and service employment in proportion to the employment potential of each zone, subject to capacity constraints on the amount of land use accommodated in each zone. The model ensures that population located in any zone does not violate a maximum density constraint which is fixed on every zone. In the service sector, a minimum size constraint is placed on each category of service employment, and the model does not allow locations of service employment to build up which are below these thresholds.

Having located the various activities, the model ensures that the population and employment distributions, used to calculate the potentials, are consistent with the predicted distribution of population. Consistency is secured by feeding back into the model predicted population and employment and reiterating the whole allocation procedure until the distributions input to the model are coincident with the outputs.

In 1966, Garin (1966) published an important paper. He suggested to replace the potential models by production-constrained gravity models and substituted another economic base mechanism for the analytic form. Consequently, the coupling between allocation and generation was much improved. In line with the quantitative revolution in urban planning, the model was elaborated in several directions and gave rise to many similar models. We will discuss some of these below.

In reaction to this paper, and in line with the dominant modelling tradition at that time, the allocation of land use and the prediction of related spatial behaviour were established by using spatial interaction models. For example, Crecine (1964) developed a model, called the Time Oriented Metropolitan Model (TOMM). He adopted the same basic structure of the Lowry model, but enforced a disaggregation of population into different socio-economic groups to increase the explanatory power of the model. In addition, time was treated in a different manner. Whereas the Lowry model assumed that all activities respond to changes in potential in a given projection period, the TOMM model assumed that only a certain proportion would respond to account for inertia. In a later version, Crecine (1968) further suggested to replace population and employment potentials by linear equations relating site rent, transport cost and other site amenities such as the availability of schools.

Another example is The Projective Land Use Model (PLUM) was designed by Goldner (1971) for the Bay Area Transportation Study Commission. The contribution of this model concerns replacing potentials by gravity models to allocate land uses. More specifically, the model allocates services and population using intervening-opportunity models. In addition, Goldner disaggregated the parameters for each of the nine counties in the Bay Area and used zone-specific activity rates and population-serving ratios to account for differences in population and employment structure. It reflects a more general tendency to use disaggregation
and a wider set of parameters in an attempt to make the models more realistic, which made them also more of a black box and a data-fitting exercise.

Perhaps the most widely used model is ITLUP/DRAM/EMPAL/METROPILUS. ITLUP represents the first fully operational integrated transportation and land use package (Putman, 1983). The land use model was a modification of Goldner’s version of the Garin-Lowry model of land use and the network model was a conventional capacity-constrained incremental assignment model. A preliminary allocation of land use activities was used to produce trip matrices. The resulting travel times were used to calculate new activity distributions. Later, the land use model was revised by modifying the spatial allocation equation. This became known as DRAM and EMPAL, which in the early 1990s were the most widely applied land-use models in the United States. DRAM locates households, while EMPAL locates employers/employees. While these models did not have the most theoretically comprehensive structures that could be imagined, apparently they met some needs in the field. After the initial model implementation projects, during which the models were installed on agency hardware, calibrated to regional data, and applied in forecasting by the agencies, about half the agencies continued with in-house use of the models as a component of their ongoing land-use and transportation and forecasting analyses. In the 1990’s, modified versions were developed and distributed as METROPILUS. It is embedded in a GIS environment, and was first used for student projects. Other but similar models include The Leeds Integrated Land-Use model (Mackett, 1983, 1990, 1991b) and the IRPUD model was developed for the city of Dordmund Michael Wegener and his co-workers (Wegener, 1982a, b; Wegener, 1983; Wegener, et al., 1991).

In the 1970s, the spatial interaction model was gradually replaced by discrete choice model. One of the main reasons was that the parameters of the spatial interaction model could not realistically be interpreted in terms of preferences and utilities and hence did not have a sound foundation in theories of individual choice behaviour. As a result, since the 1970s, there was a gradual and incremental shift in the modeling basis of integrated land use-transport models as well. Examples are MEPLAN and especially TRANUS.

The MEPLAN model was developed by Echenique and Partners through a series of studies in different countries in the world. It started with a model of stock and activities (Echenique, et al, 1969), followed by the incorporation of a transport model developed for Santiago, Chile (de la Barra, et al, 1975), the incorporation of an economic evaluation system for Sao Paulo (Flowerdew, 1977), the representation of market mechanisms in the land use model for Tehran (Horton and Echenique, 19789), the incorporation of an input-output model, again for Sao Paulo (Williams and Echenique, 1978), and the more comprehensive model, developed for Bilbao (Geraldes, et al, 1978).

At the heart of the system is an input-output model to predict the change in demand for space (Echenique, 1994). The coefficients of the input-output are elastic with respect to prices and incomes. A spatial system is used to allocate the demand to spatial zones, using random utility concepts. Spatial choices link production to consumption, generating the demand for transport. An equilibrium model is derived by solving all the equations, subject to constraints. Given transport demand by type and flow, the transport model predicts modal split and assignment, with adjustment for times for capacity constraints. Again, random utility concepts are used in the transport model. Information about costs, travel times due to congestion, etc are fed back into the land use-economic model to provide time-lagged measures of accessibility. Hunt (1994) describes the application of the model in Naples. Echenique, et al (1995) used the model to simulate the effects of urban policies.

The Tranus integrated land-use and transport modeling system was developed to simulate the probable effects of applying particular land-use and transport policies and projects, and to evaluate their social, economic, financial, and environmental impacts. A detailed explanation can be found in de la Barra (1989) and in Modelsica (1999). Tranus has a land use or activities model and a transport model. It is assumed that activities compete for real estate, resulting in equilibrium prices. The location of activities is influenced by such prices, but also by
accessibility, generated by the transport system. The location of activities is modeled in the land use system. The transport model uses travel demand as input and assigns it.

The land-use model is basically a spatial input-output model. The activities are divided into sectors, such as productive sectors (agriculture, mining, industry, services, etc.), and households (by income or size). The demand for each sector or land use is determined in a flexible way. Once total demand has been determined for each demand zone and sector, it is distributed to production zones and sectors, according to a multinomial logit model, subject to possible constraints. If total production in a constrained sector and zone is greater than the maximum, the equilibrium price is increased; if it is less than the minimum, the equilibrium price is decreased.

A supply model is used to simulate the expected behavior of land and floor space developers. Developers in a specific zone may choose between developing new land (if available) into high- or low-density residential use or for commercial use. They may also substitute land uses. Such processes are estimated with another set of logit models in which the utility function includes the expected price or rent of the new stock, the price of the stock being replaced, demolition costs, building costs, and so on. Land-use controls may be introduced to constrain this process.

The land use model generates a set of matrices of flows representing potential transport demand. The purpose of the transport model is to transform potential demand into actual trips, and to assign these to the transport supply options. Generalized costs of each path are calculated as is the degree of overlapping between paths to ensure that the results represent distinct travel options. Generalized costs are recalculated in an iterative process to account for changes in travel and waiting times due to congestion.

In this process, potential travel demand calculated by the land-use model is transformed into actual trips at a particular time of the day (peak hour, twenty-four hours, etc.) by transport mode as an elastic function of cost. Next, modal split is estimated using a logit model (a combined trip generation – model split also exists). Trips for each category are assigned to the different multimodal paths connecting origins to destinations. Since each path implies a particular sequence of modes and transfers, trips are simultaneously assigned to modes as well as to links of the network, using another logit model, where the utility functions are determined by the overlapped generalized cost of each path. By applying vehicle occupancy rates, trips are transformed into vehicles by mode in each link of the network. Public transport is assigned directly to the network. In turn, the number of vehicles by operator is transformed into standard vehicles by applying appropriate rates. The final stage of the iterative process is a capacity restriction procedure, in which travel speeds are reduced and waiting times are increased in every link for each route as a function of demand/capacity ratios. Waiting times take into consideration the frequency of transit services and the demand/capacity ratio of the vehicles themselves. This iterative process continues until convergence is achieved.

The theoretical concept of random utility theory was also used in several other models developed until very recently, some of which in fact are still under development. Examples include the California Urban Futures Model (CUF), earlier known as the Bay Simulation System (BASS), (Landis, 1994; Landis and Zhang, 1998a,b), MUSSA developed by Martinez (1992, 1997) RURBAN model (Miyamoto, et al, 1986; Miyamo and Udomsri, 1996), CATLAS and METROSIMA (Anas, 1982, 1983) (Anas, 1994), and DELTA developed by David Simmonds Consultancy, MVA Consultancy and the Institute of Transport Studies, Leeds during the period 1995-1996, building on the START model (Bates, et al, 1991).

The state-of-the-art in this field is perhaps best represented by UrbanSim. The initial design of the UrbanSim model was funded by the Oahu Metropolitan Land-Use Model as part of a larger effort to undertake the development of new travel models. The project involved the development of a travel model system based on modelling tours rather than trips. The model was further elaborated in 1996 when the Oregon Department of Transportation launched the Transportation and Land Use Model Integration Project (TLUMIP) to develop analytical tools to support land-use and transportation planning. The model was extended and a prototype was implemented. The model was calibrated for a case study in Eugene-Springfield.
Later, the dynamic aspects of the model were calibrated, and the model was applied in Utah and Washington (Alberi and Waddell, 2000; Waddell, 2002).

The model claims to simulate the key choices of households, businesses, developers and governments and their interaction in the real estate market. A demographic transition model simulates changes in the population and iterative proportional fitting is used to create households of particular types. An economic transition model is establishing the same for business sectors. Household and economic mobility models are used to simulate whether households and firms decide whether to move. Movement probabilities are based on historical data. A multinomial logit model is then used to allocate new and moving households to residence locations and jobs to job locations. Variables used in the household location model include attributes of housing in the grid cell (price, density and age), neighbourhood characteristics (land use mix, density, average property values and local accessibility to retail) and regional accessibility to jobs. The employment location model includes real estate characteristics in the grid cell (price, type of space, density and age), neighbourhood characteristics (average land values, land use mix and employment in each sector) and regional accessibility to population.

A real estate development model simulates development choices (including not developing) about new development and redevelopment, using a multinomial logit model. Variables include characteristics of the grid cell (current development, policy constraints and land and improvement values), characteristics of the site location (proximity to highways, arterials, existing development) and regional accessibility to population. The land price model simulates land prices of each grid cell as the characteristics of locations change over time, using hedonic regression. A logsum accessibility measure is used, calculated by a travel demand model system.

An examination of the history of integrated land use – transport models suggests that after some time lag, the state of the art in modelling transport demand are incorporated into the integrated land use – transport models. Hence, since activity-based models of transport demand have become the research frontier since the mid 1990’s (see Timmermans, et al 2002 for an overview), plans have been announced to develop activity-based, micro-simulation methods. Fully integrated models do not exist yet, but some progress has been made. One ongoing research programme focused on the development of activity-based integrated land use and transport models is the Integrated Land Use, Transportation, Environment (ILUTE) modelling system which is under development by a consortium of researchers in Canada from the universities of Toronto, Calgary, Laval and McMaster (Miller and Savini, 1998). It represents an experiment in the development of a fully microsimulation modelling framework for the comprehensive, integrated modelling of urban transportation - land use interactions, and, among other outputs, the environmental impacts of these interactions. As of to date, only some of the key aspects of the envisioned system have been reported in the literature. It differs from earlier work in a number of important ways. First, it differentiates between persons and households. Secondly, the urban system state evolves over time from an assumed known base year and no particular assumptions concerning system equilibrium are required. Thirdly, it differentiates between firms, which are modelled as agents. Fourthly, in addition to zones, buildings are recognized. Finally, as indicated, activity-based models of transport demand replace the simpler trip or tour-based models. The goal here is to develop a model, which schedules individuals’ activity-travel patterns within a household context, which requires some original work as most current activity-based models are fundamentally person-oriented. Moreover, the goal is to develop multi-day models as opposed to the single day models that dominate the field.

Within ILUTE a consistent conceptual structure is applied to modelling individual consumers within a given market. This involves of a three-stage process consisting of (i) the decision to become active in a market, (ii) search and (iii) bidding and search termination. The envisioned model system represents an attempt to combine such of the latest approaches in transport modelling, such as an activity-based approach. To some extent, the plans go beyond the incorporation of such a model in that some of the concepts that are discussed still need ground-breaking original research.
Another example is Ramblas, a system developed to estimate the intended and unintended consequences of planning decisions related to land use, building programs, and road construction for households and firms (Veldhuisen, et al., 2000). The model allows planners to assess the likely effects of their land-use and transport plans on activity patterns and traffic flows. It simulates the whole Dutch population of 16 million people.

The input of the simulation model consists of the distribution of various types of households across the different kinds of dwellings per zone, and the distribution of land uses and dwellings per zone. These variables are external to the simulation. Changes in these variables are externally monitored. Households are classified according to their size, and for each class the age and gender of household members are calculated. The spatial attributes of the area (i.e., land use, dwelling stock, and road system) are treated as variables that can be manipulated by planning. The planning of the road system is also dependent on decisions of the various planning authorities. The spatial distribution of activities and trips are treated as dependent variables. Thus, the model enables us to predict the likely consequences of possible policy decisions on activity patterns and thus estimate the effectiveness of such policy decisions. In particular, these decisions concern changes in land use, dwelling stock, and road construction.

The aim of the micro-simulation is to predict which activities will be conducted where, when, and for how long, the transport mode involved, and which route is chosen to implement the activities. National data are used for this purpose. The first step in the micro-simulation then involves for every individual in the study area to (i) identify the corresponding population segment, and (ii) draw at random from the national distribution the activity agenda and transport mode. Population segments were identified on the basis of gender, age, employment status, and educational achievement. Twenty-four different segments are used. Seven activity classes are distinguished: work, child care, shopping, personal/medical care, school or study, social participation, and social contacts. For each of these out-of-home activities, the distribution of chosen transport mode is derived.

Using this data, the first step of the micro-simulation results in an activity agenda for a simulated individual. The next step of the simulation addresses the problem of how this agenda is implemented in space and time. To that end, various additional operational definitions that drive the allocation of activities to particular destinations were made. In the case of the work activity, it is assumed that the travel time observed in the diary constitutes the time people are willing to travel to work, given the transport mode involved. In terms of the micro-simulation, this means that a zone of employment is drawn at random from the total number of available jobs in the region, delimited by this maximum travel time. Job locations are drawn without replacement, hence the set of job locations is reduced during the simulation.

In the case of study, a different principle is employed. It is assumed that children going to elementary schools invariably choose the school nearest to their residence. Although this assumption is not perfect, it reflects the planning of the school districts in the Netherlands. For students going to secondary schools, an action space of 45 minutes of bicycling time is assumed. Schools are drawn at random from this action space. The same principle is used for students of higher education, but now the distribution of employment in higher education is used as the distribution from which the school is sampled.

The latter principle is also used to determine the destination for shopping and services. The destination is drawn at random from the distribution of employment in the relevant services. As for the final activity classes, social participation, and social contacts, the presence of other households rather than employment, is used as the distribution from which the destination is sampled.

Having established these origin-destination pairs, the next step of the simulation involves the micro-simulation of traffic flows. Travel time is simulated using the "speed-flow" calculation method. For every chosen interval, the traffic flows are graphically displayed on the computer screen.
**Discussion**

The brief overview of some of the literature indicates that the relationship between land use change and transportation is treated in a different way in these modelling approaches. In cellular automata models, the transportation network is given, and land use change is usually modelled as a function of accessibility to the transportation network. The reverse link of the coin is usually not modelled. However, in principle one could link a cellular automata model to some type of transportation demand model. For example, traffic generating functions could be assigned to different land uses, and the resulting traffic be simulated on the network, calculating congestion, which could then be used in turn to adjust the transition probabilities. One should keep in mind however that such an approach lacks theoretical integrity. Moreover, recent developments in modelling destination choice and transport demand are much less easy to incorporate in cellular automata models.

The value of such models also depends on the purpose of their use. If the goal is not to predict or simulate as closely as possible the future, especially on the local level, but rather as part of scenario develop better understand urban evolution, CA models may be useful in plan development session. Because they do not require much data and can be run fast, they also may have some advantages in application settings with data scarcity.

If one the other hand, the goal of the application is to have as realistic as possible forecasts, it seems one needs a more sophisticated model. In this context, the state-of-the-art integrated land use transportation models lags behind in the sense that many recent advances in modelling transport demand still have to be incorporated into these integrated models. Also, the central role played by accessibility is questionable in this regard. Also, it may be better to treat new planned land use as a given, rather than trying to predict all future land use exogenously.
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