The Saga of Integrated Land Use-Transport Modeling: How Many More Dreams Before We Wake Up?

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1. Introduction

The division of labour in modern societies has resulted in a spatial allocation of functions, such as residences, shops, restaurants, leisure facilities, etc. In order to survive and to conduct their preferred activities, individuals, households and firms have to travel. The spatial distribution of land use (planned or unplanned) constitutes the choice set from which individuals can pick the destinations where they wish to conduct the activities they need or desire to perform. Although spatial land use patterns restrict individual choices, it seems that in many situations a relatively large degree of freedom still remains to choose the preferred destinations. Empirical evidence tends to suggest that the relationship between characteristics of land use patterns and aspects of mobility is weak. Thus, land use patterns seem to provide opportunities to travel as opposed to dictating travel behaviour. If public transport does not exist in a particular neighbourhood, people cannot use it; it if does exist, people don't necessarily use it.

Land use patterns thus impose constraints and offer opportunities for people to conduct their activities, resulting in particular activity-travel patterns. Similarly, the choice of destination is often a key factor for the feasibility of particular functions at particular locations. If people decide to start choosing for example other shopping locations, certain stores or shopping centers may disappear, resulting in a changing land use pattern, which in turn may induce shifts in travel behaviour. Also, exogenous change may result in changing land use patterns and hence changing activity-travel patterns.

One would therefore expect a strong tradition in transportation and urban planning of developing integrated land use-transport models. However, depending on one's point of view, this is not really the case. Although several transportation researchers and urban planners have developed integrated land use-transport models since the 1960s, it always has been a subdominant field of interest, especially compared to the modelling of various aspects of transport demand, which typically treated land use as an exogenous variable of the model. In fact, most early work stems from urban planning, but in that discipline, the interest has virtually disappeared completely, although lately there is some evidence of renewed interest.

To stimulate the discussion, the guiding postulate underlying this present paper is that one needs to be a die hard to become involved in this area of research. Integrated land use - transport models attempt to predict (the dynamics) of land use patterns and travel patterns, and their interaction. Consequently, the topic area is inherently very complex and thus difficult to model, requires a tremendous amount of data, and hence time before any test can be performed, and the integrated models are costly to implement because the responsible planning agencies need to invest in people, data and equipment to collect and update the data. There seems insufficient support for such investment, especially because the field has not succeeded in commercialising the short-term forecasts of traffic flows. Thus, it seems that integrated land use - transport models should find their relevance in supporting long term, strategic planning decisions. However, in a particular city, such decisions are often infrequently made and hence the return on investment is potentially low. In other words, both from an academic perspective and an applied perspective, on might argue that there is a relative lack of incentives to become heavily involved in this area of research.

Moreover, to stimulate the discussion, we will argue that from an academic point of view not much fundamental progress has been made since the 1960s. Although the newest generation of land use-transport models is using the latest GIS technology and we have seen three waves of modelling attempts, the fundamental problems identified in the 1970s still largely remain to be solved. So, when will we wake up, start addressing the key problems of this research area, and perhaps have a more realistic perspective on the potential relevance and application of this research area?

It goes without saying that this overview of existing models is limited. We will not discuss all models or all modelling approaches. We focus on the models that have received most attention in the literature and that can often be considered as examples of a specific approach. This means that we will not discuss the many, especially older, variants of aggregate models, models developed by planning authorities such as ULAM in Florida, and models that have not gained momentum such as CARPE and other models, based on Forrester's urban dynamics (Bertuglia, *et al*, 1981, 1987; Fournier, 1986), Wilson's catastrophe model (Wilson, 1981), older normative models such as TOPAZ (Brotchie, *et al*, 1980), POLIS (Prastacos, 1986a,b), Kim's model (Kim, 1989), STASA, based on the master equation approach (Haag, 1990), many cellular automata models, and the various models on land use change, developed in the environmental sciences.

This resource paper is organized into four sections. The first three sections summarise the first three generations of land use-transport models. First, we will summarise the models based on aggregate data and principles of gravitation and entropy-maximisation. This is followed by models, based on the principle of utility-maximisation. Next, we will briefly summarise some of the most recent models under development, based on micro-data and activity-travel patterns. Based on this summary, we will then discuss some of the key issues that seem to hamper a fundamental breakthrough in this area of research. Finally, we will draw some conclusions.

2. The first wave: aggregate spatial interaction-based models

The Lowry-Garin model

One of the first models that gained substantial interest 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.

TOMM

The first derivate of Lowry's model was developed by the CONSAD Research Corporation as part of the Pittsburgh Community Renewal Program (Crecine, 1964). This model, called the Time Oriented Metropolitan Model (TOMM), adopted the same basic structure 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.

PLUM

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.

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.

LILT

The Leeds Integrated Land-Use model (Mackett, 1983, 1990, 1991b) combines a Lowry type location model with a four-stage aggregate transport model. Forecasts of total change in population, new housing and jobs are allocated to zones according to accessibility functions and the attractiveness of the zone, using entropy-maximizing principles. Employment is disaggregated into twelve sectors, while population is divided into three socio-economic groups. The model handles demolition, changing occupancy rates and vacancies. Car ownership is estimated as a function of time and travel costs. Trips for work, shopping and other purposes are allocated to car, public transport and walking. Capacity-constrained road assignment is used, implying that speeds are a function of traffic flow.

IRPUD

The IRPUD model was developed for the city of Dordmund Michael Wegener and his coworkers (Wegener, 1982a,b; Wegener, 1983; Wegener, *et al.*, 1991). A macroanalytic model of economic and demographic change is used to simulate employment change by industrial sector and demographic changes by age, gender, and nationality within a set of labour market regions. Given this model, a mesoscopic spatial model is used to simulate intra-regional location decisions of industry, residential developers and households. Finally, a micro-analytic model of land use development within statistical tracts is used to allocate the demand generated by the mesoscopic model.

The simulation involves seven interlinked submodels that deal with aging of people, households, dwellings, and workplaces; relocation of firms, redundancies, and new jobs; nonresidential construction and demolition; residential construction, rehabilitation, and demolition; change of job; change of residence, and car ownership and transport. The transportation and land use subsystems are maintained separate. Mode choice is nested within destination choice and takes into consideration car availability and generalized travel costs. A distinction is made between discretionary and non-discretionary travel, using respectively doubly constrained and production-constrained entropy-maximizing models. The spatial distribution of land use is allowed to change through aging (using a Markov process), exogenous events and accessibility based spatial choices generated explicitly within the model. The use of gravity models make the model one of the first generation. However, the use of microsimulation is more typical of the latest generation of land use-transport models.

3. The second wave: utility-maximizing multinomial logit-based models

The MEPLAN model

This 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 (Hirton 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.

TRANUS

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 Modelisrica (1999). Tranus has a land use or activities model and a transport model. It is assumed that activities compete for real estate, resulting in equilibium 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 multi-modal 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.

BASS/CUF

As indicated by Landis (1994), the California Urban Futures Model (CUF), earlier known as the Bay Simulation System (BASS), was developed to simulate how growth and development policies might alter location, pattern and intensity of urban development. The model differs from the typical integrated transport-land use model in a number of ways. First, regional forecasts are not allocated, but a bottom-up approach is followed. Secondly, development is not only a function of spatial accessibility but of a wider set of variables. Central to the model is the notion of the profit potential of each developable land unit as a function of sales price, raw land price, hard construction costs, site improvement costs, service extension costs, development, impact, service hookup and planning fees, delay and holding costs and extraordinary infrastructure capacity costs, extractions and impact mitigation costs. CUF-2 (Landis and Zhang, 1998a,b) consists of two multinomial logit models of land use change. The first submodel explores the determinants of land use change among undeveloped sites, while the second model examines the determinants of land use change among previous developed sites. The probability of land use change is a function of initial site use, site characteristics, site accessibility, community characteristics, policy factors and relationships with neighbouring sites.

MUSSA and RURBAN

This model, developed by Martinez (1992, 1997) received some interest because the spatial allocation of land uses is handled using a bid function. The model is not a fully integrated model, but can accept as input the total demand (growth) from households and firms and a transport model. Central to the model then is to predict the location of households and firms and the resulting rents. To that effect, following Ellickson (1981), a bid function is used, which is specified as a function of property attributes, zone attributes, transport attributes and consumer clustering variables. He showed that the spatial probability distribution obtained from the bidding function is identical to the probability distribution obtained by the maximisation of individuals' (consumer) surplus, emphasising the equivalence of the bid and choice approaches, given the traditional set of assumptions. Operationally, a multinomial logit model is assumed. The reliance on bid rent is similar to the earlier developed RURBAN model (Miyamoto, *et al*, 1986; Miyamo and Udomsri, 1996)

CATLAS and METROSIM

The Chicago Area Transportation – Land Use Analysis System (Catlas) was developed by Anas (1982, 1983) for studying the relationship between land use and transportation. It differs from previous attempts in that it was better rooted in economic theory. The system consists of four submodels that are all derived from discrete choice theory and utility-maximizing behaviour: 1. a demand submodel, 2. an occupancy submodel, 3. a new construction submodel and 4. a demolition submodel. The model predicts the probability that a worker employed at a workplace will live in some residential zone and the conditional probability that he will commute by some transport mode. The housing supply submodel calculates the probability that the average dwelling in each zone will be offered for rent in a particular year as a function of average rents in that zone and various zonal attributes. New construction and demolition depends on construction costs, expected future resale values, current and future taxes, operating costs and land prices. The demand and supply submodels are estimated only for two workplaces: the CBD and the rest of the Chicago SMSA. A multinomial logit model is used to predict four modes (car, commuter rail, rapid transit and bus) for the CBD and only car and bus for the remainder of the study area.

Building on the CATLAS model of combined residential location, housing and mode choice, the modelling of non-work travel choices and commercial real estate markets in the New York region (the NYSIM model), and the modelling of metropolitan housing market dynamics in a number of US cities (the CHPMM model), Anas and his colleagues have developed a highly integrated economic model of transportation and land use called METROSIM (Anas, 1994). This model consists of 7 sub-models, providing analysis of a region's basic industry, non-basic industry, residential and commercial real estate, vacant land, households, commuting and non-commuting travel and traffic assignment, within a single structure.

DELTA

This model was developed by David Simmonds Consultancy, MVA Consultancy and the Institute of Transport Studies, Leeds during the period 1995-1996. It builds on the START model (Bates, *et al*, 1991). Consequently, it is not an integrated package, but a link of separate models. Input to the land use model is the accessibility and area quality output of the transport model. New to the model is that accessibility is based on accessibility from each zone to alternative destinations for each variety of purposes. Log-sum type of accessibilities are used. Land use change is modelled for demographic change and employment change. Demographic change is primarily modelled in terms of household formation, dissolution and transformation. The economic growth model applies sector growth or decline rates to each sector in each zone and specifies which proportion is mobile during the current period. These rates are exogenous to the model. The location model predicts the location of those activities that are mobile as a function of accessibility, transport-related change in the local environment, area quality and rent of space.

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.

IMREL

The integrated Model of Residential and Employment Location was developed in close connection with Office of Regional Planning and Urban Transportation of Stockholm (Anderstig and Mattson, 1991, 1992, 1998; Boyce and Mattsson, 1999). The models starts with the total number of households and the total number of workplaces, given at the regional level. These are not predicted as part of the model but exogenously given. These totals are then distributed across a system of zones through a process of interactions between a residential and an employment location sub-model. These sub-models use as input data, among other things, travel times and travel costs between zones by available models of transport as calculated by a traffic assignment module of a linked travel demand model. The residential location model predicts the combined choice of residential location and travel mode, given the employment location. The predicted land use changes are fed back into the travel demand model to make sure that the travel times and costs for the car mode are consistent with the input car travel times and costs. The residential location model allocates the regional population to zones such as to maximize a welfare measure based on locational consumer surplus, subject to lower and upper bounds, using a nested multinomial logit model.

The employment submodel predicts how employment location depends on accessibility to the labour force and other indicators of zonal attractiveness. For given travel characteristics, iterations are carried out between the two models until the residential and employment patterns stabilize. Two categories of employment are considered: local services and other. A multinomial logit model is used to allocate the workforce to the zones. Shadow prices are added to the attractiveness of the zones to ensure that the imposed bounds on the number of work places will not be violated.

IMREL is as opposed to most other land use models a normative model on the residential location side. That is, given the location of workplaces, and given the transport system (which gives the travel times and travel costs between different zones by different modes), the model finds the location of a predefined number of housing units that maximises the total expected utility achieved by the households given endogenously determined equilibrium housing rents while, at the same time, observing any given upper and/or lower bounds on the number of housing units that is allowed to be located in each zone. It was shown (Boyce and Mattson, 1999) that this approach can be made consistent with user equilibrium behaviour in the road network.

TILT

Using similar utility concepts, the same group also developed the TILT model (Eliasson, 2000; Eliasson and Mattsson, 2000). Unlike IMREL, this model is descriptive by nature. It models how the households, workplaces, shops, service establishments would locate and interact, without any claim that the aggregate behaviour is optimal.

Uplan

UPlan (Johnston, *et al,* 2003) allocates the increment of additional land in user-specified discrete categories consumed in future years. County or regional land consumption are calculated endogenously. It allows the user to input demographic and land use density factors that are converted to hectares (ha) of land consumed for each land use. To determine ha needed for future housing, the user specifies persons per household, percent of households in each density class, and average parcel size for each density class. A similar conversion is used to determine ha of land consumed for industry and commerce and uses workers per household, percent of workers in each employment class, and average land area per worker. These calculations produce a table of land demanded, for each land use type, from which the model operates its land allocation routine.

A suitability grid influences future land use change. Users can attach a weight to indicate the attractiveness of each cell, as a function of for example proximity to existing urban areas and transportation facilities, such as freeway ramps. Users can also specify cells where development cannot take place.

The model allocates future development starting with the highest-valued cells. As the higher-valued cells are consumed, the model looks for incrementally lower-valued cells until all ha of projected land consumption are allocated. Users can decide on the order in which land uses are allocated. Low-density residential land use is randomly allocated throughout available rural areas to represent the prevalent non-contiguous pattern of exurban rural development.

In a recent test application for the Sacramento region, Uplan was linked to a travel demand model to include the effects of changing accessibility, measured in terms of a logsum (user benefit). These accessibilities were into Uplan to make a zone with a higher accessibility more attractive for development.

4. The third wave: towards activity-based, micro-simulation models

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.

ILUTE

One ongoing research programme focused on the development of activity-based integrated land use and transport models is the **I**ntegrated **L**and **U**se, **T**ransportation, **E**nvironment (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.

Ramblas

The system is 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 is 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 of school, 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.

The Irvine simulation models

Based on McNally (1997, 1998), Kulkari and MacNally (2000) suggested a simulation model of activity-travel patterns that closely resembles the core of the Ramblas model. One important difference however is that their model is based on a classification of representative activity-travel patterns. In common with Ramblas, however, some key aspects of such patterns are extracted from the data and used to simulate activity-travel patterns in a particular environment.

More recently, the group is exploring the use of multi-agent systems (e.g., Marca, *et al*, 200; Rhindt, *et al*, 2003). The scope is similar to ILUTE, but the methodology that is used seems different.

ILUMASS

The integrated land-use modelling and transportation system simulation project aims at a microscopic dynamic simulation of urban traffic flows into a comprehensive model system, which incorporates both changes in land use and the resulting changes in transport demand (Moeckel, *et al*, 2002). Microsimulation is used to trace demographic development, household formation, firm lifecycles, construction of houses and buildings, and labour and household mobility. These modules are linked to models of daily activity patterns and travel and goods movements. Work on developing this model has just started.

Cellular automata and multi-agent models

As indicated before, the initial interest in comprehensive urban models more or less disappeared in the 1970s. First, there hardly seemed any research effort in this field at all, but after a decade or so, inspired by complexity theory and the theory of self-organising systems, a large number of cellular automata models were developed (e.g., Batty and Xie, 1994; Cecchini, 1996, Clarke and Hoppen, 1999; White and Engelen, 1993; Batty, *et al*., 1997). In most of these models, the transport component is weak. Typically, a network is assumed, but traffic flows are not simulated. More recently, however, some scholars announced plans link their cellular automata model with a transport model.

Central to these models is the use of cells, which can occupy particular states. Originally, cellular automate models were based on cells with two states only, but more recently models involve more cell states. States could for example be a set of different land uses. Cell states may evolve according to transition rules, which can either be deterministic or stochastic. In many applications, however, not all possible transition between states are defined but one usually suffices with a subset of possible transitions. Traditionally, dynamic processes over space were simulated for the eight neighbouring cells, but more recently applications which use circular neighbourhoods of a wider radius have been suggested (e.g., Engelen, White and Uljee, 1997).

In applications to land use patterns, transition rules represent locational preferences and spatial interaction mechanisms. The interaction mechanisms are usually depicted in terms of distance decay functions. For a particular interaction between pairs of cells or for other spatial resolution, transition weights are specified. For each cell then, the potential for transition is calculated. Engelen, *et al* (1997) for example used the following equation:

$$P_z^t = u q_z A_z N_z$$

$$N_z = \sum_d \sum_i w_{z,y,d} I_{d,i}$$

$$u = 1/(1 + [-\ln(rand)]^a)$$

where,

P_z^t is the potential for transition to state z;

u is a stochastic disturbance function;

q_z is the suitability of the cell for state z ($0 \le q_z \le 1$);

a_z is the accessibility of the cell for state z to the nearest cell of the transportation network;

w is a weight for cells in state y in distance zone d;

$I_{d,i} = 1$ if cell i in distance zone d is in state y, otherwise $I_{d,i} = 0$;

Cells will change to the state for which the potential is highest until the demand for cells in that state is met.

Note that the above formulation identifies two factors influencing the transition potential, constrained by a cell suitability factor: the interaction factor and the accessibility factor. The latter factor is expressed as:

$$a_z = 1 / (1 + R / a_z)$$

where,

R is the distance from the cell to the nearest cell of the transportation network;

a_z is a parameter expressing the importance of good accessibility to the transportation network.

The former factor can be specified for each cell, but usually will be represented by a distance decay function (White and Engelen, 1993). If one chooses this option, implicitly one assumes that the interaction can be represented by single-stop, single purpose trip behaviour.

Most cellular automata models have been developed to simulate urban growth and urban change, often to illustrate theoretical principles. However, this brief summary illustrates that many of the principles underlying integrated land use – transport models are also incorporated into cellular automata models or can be easily incorporated by linking the model to a transport model. Even in that case, however, the cells are not decision-makers. Recently, therefore, a shift towards multi-agent systems can be detected.

The first of these is SIMPOP (Bura, *et al*., 1996; Sanders, *et al*., 1997), which views every cell as an agent, and therefore is best considered as a special case of a cellular automata model as opposed to a true multi-agent model. The inheritance property is used to build up a hierarchy of type of agents with nested properties. Rules are used to model the change, which will occur in each cell. The rules refer to the state of the cell itself and to the states of the neighbouring cells.

Ongoing work, however (e.g., Arentze and Timmermans, 2003) has developed negotiation protocols to model how different agents compete for the same locations or take advantage of synergy. In another project, Arentze, Katoshevki and Timmermans (2003) have developed a prototype of a system, called Absolute, that links an activity-based model of transport demand to site selection decisions of firms as part of a wider model of land use decisions and land use change. It seems therefore that the first evidence of a merging or combination of these different modelling approaches is accumulating.

5. Wake up?

The introduction of large scale urban and regional models in the 1960s led to high expectations about their relevance and success. Finally, land use and transportation planning practice had the tools to replace its intuitive style to one based on scientific principles. It only took a decade when Lee (1973, 1994) voiced the view that these efforts had essentially failed. It meant the end of the first generation of large scale models, especially in the urban planning literature. The models were accused of being too data hungry, non-transparent and in need of costly computer hardware. Moreover, the planning style had changed from a centralized planning to incremental planning.

Large-scale models however did get a second chance primarily as an academic activity in the 1990s. Advances in random utility theory, discrete choice modelling, network equilibrium models and geographical information systems led to new models. Some authors (e.g., Anderstig and Mattson, 1998) have argued that these developments have been helpful in combating the block box syndrome and increased the transparency of applied models. While it is true that the models can now be interpreted in terms of a simple underlying theory, the more fundamental criticism still remains. Although some models replaced the spatial interaction model component by a multinomial logit model, many essentially remained aggregate in nature, and therefore might as well be characterized as an entropy-maximizing models as opposed to a discrete choice, utility-maximizing models. Moreover, there is little proof that progress in spatial choice modelling, especially related non IIA models, has been incorporated into integrated land use – transport models. It is a strange experience to notice that at symposia on integrated land use –transport systems often basic principles that were discussed in more specialized models considerable time ago, are still high on the agenda, while the contributing fields have moved along and started to work on the next generation of models. We agree with Waddell (2002) that integrated land use –transport models have benefited from advances in computation and econometric methods, allowing a general tendency of disaggregation of household and land use classification, a shift from equilibrium to disequilibrium, and from census tracts to grid cells. Moreover, the availability of geographical information systems has certainly improved the visualization of land use change and therefore the user-friendliness of the systems. At the same time, however, if this indeed is a good description of progress, it demonstrates that the behavioural, theoretical underpinnings are still weak, that theory has been largely borrowed rather than specifically developed for the problem at hand, and that some of the old fundamental problems still have not been solved. What should be done before this area of research can be called mature and if that could be accomplished what should be our realistic expectations about the potential use of such models?

Dream 1: Inducing principles of spatial behaviour

To the extent that integrated land use – transport models are estimated from empirical data, distance decay functions (or accessibility functions) are typically derived from data on destination choice for specific travel purposes. Nothing has change in this regard from the early inception of land use –transport models to the most recent attempts. This practice, however, constitutes a fundamental problem, both theoretically and in terms of application/forecasting. As we have argued in the introduction to this paper, space offers both opportunities and constraints. Only if spatial structure allows individuals and households to implement their preferences, observed spatial choice behaviour can be viewed as a manifestation of consumer preferences and be conceptualised in terms of utility-maximisation. Distance decay functions are used to express sensitivity to distance. However, we know this is not true. Sometimes, people have to travel further distances to reach the nearest destination; the provision of facilities classified according to some variable influencing choice behaviour is often not independent from distance, implying that the decomposition of these two effects on spatial behaviour is often quite problematic. It means that distance decay functions do not describe the principles underlying spatial choice behaviour (or better sensitivity to distance, travel time or accessibility) but some unknown mixture of spatial preference and spatial structure.

- The implication of this is that estimated distance decay and utility functions cannot be validly used for forecasting the impacts of planning decisions. By their very nature, planning decisions will change spatial structure and therefore the antecedent conditions for observations of spatial choice will be different.
- This argument that the parameters of spatial interaction and spatial choice models are highly influenced by the geometry of the study area is in fact quite old (e.g., Rushton, 1969; Curry, 1972; Ewing, 1974; Sheppard, 1979). Veldhuisen and Timmermans (1979) using numerical simulation demonstrated that when the same set of principles is used to generate trip patterns in study areas of different structure, the estimated parameters indeed are not the same but differ between study areas. In fact, this problem was one of the early motivations to develop stated preference models (Louviere and Wilson, 1978; Timmermans, 1980).

A generally accepted solution for this problem has not yet been put forward. Moreover, progress in spatial choice analysis has shown that spatial choice behaviour is context-dependent. Hence, we need an approach that would allow use to disentangle the effects of spatial structure and spatial preference, for different sets of conditions. How can this be accomplished?

For some types of behaviour, such as the work commute, individuals often do not have a choice but can only accept (or not) a job offering. Distance, travel time or accessibility is then not an element in the decision, it follows from accepting the job offering. Hence, rather than using some distance decay effect, one could argue that individuals will base their decision on a more vague concept such as "reasonable travel distance" that is perhaps traded-off against the characteristics of the job but not against distance to other job locations. Individuals are distance-indifferent within such a band.

For other types of behaviour, such as shopping, where individuals do have a choice, other mechanisms should be developed. Regardless of the specific approach, it should ideally not be influenced by observed behaviour. Stated choice methods could be applied but the link between experimentally derived functions and behaviour in the real world is still in need of further examination. The current tendency in transportation research to use combined SP/RP data seems ill founded. If revealed preference data are, as argued above, influenced by the geometry of the study area, how then can one assume that both types of data represent the same underlying utility function? Moreover, the error terms of the stated preference model pick up other components than the error terms of the revealed preference model, implying that the theoretical foundation of rescaling these error terms is weak at best.

Dream 2: Developing context and domain-specific behavioural models

Most integrated land use – transport models rely nowadays on the multinomial logit model to predict residential choice, firms' location choice and the various destination choices underlying trip behaviour. There seems hardly any discussion on the validity of this model to these various types of choice behaviour, again illustrating the relative lack of theoretical development and the apparent focus on combining existing methodologies. If it is realised that individuals and households can only build-up utility by experiencing the options, evaluating the rewards, and thereby derive more or less stable utility functions, its is questionable that the random-utility, multinomial logit framework is adequate, let alone the most valid, for each of these types of decisions that vary considerably in their very nature. Perhaps the mode choice decision comes closely as it represents a repetitive choice and most individuals will have experienced the other options as well. The destination choice of shopping behaviour may also be reasonably modelled in terms of a multinomial logit or similar model, although multi-stop, multi-purpose behaviour is becoming increasingly more important, and spatial shopping behaviour is known to be influenced by substitution and spatial structure effects (see Timmermans, 1993 for a discussion). The assumption of time-invariant utility functions becomes questionable for the choice of destination for leisure/recreation, where variety-seeking behaviour may be quite important. Some of these effects may be picked up by replacing the trip or tour-based models with activity-based models. However, it should be realized that at the present state of the art, this would only partly solve the above problem. Virtually all existing activity-based models depend on one or two-day diaries and hence will not fully capture the notion of time-variant utility functions. In addition, the dominant utility-based models of activity-travel patterns, relying on the nested logit model, represent observed activity-travel patterns. They do not attempt to derive the principles that generate such patterns. Computational process models of activity scheduling behaviour do, but fully operational computational process models are still scarce.

Where the choice of the multinomial logit model has some possible drawbacks for modelling travel behaviour, it seems outright questionable for modelling residential choice behaviour. Households typically move only a few times in their life. Their choice sets are typically very small. They have very limited information about the housing available in the market. Search behaviour may be limited and will often be driven by forces other than distance. Different factors dictate the social housing market. Where most of the decisions related to travel behaviour are likely made by individuals, residential choice behaviour is often a family decision-making process, especially if the household consists of more members. If it is accepted that any model should at least capture the key aspects of the choice that is predicted, the multinomial logit model does not seem the way to go because it assumptions are at variance with the above characteristics.

Much better examples of modelling approaches exist in the housing literature. Micro-simulation models of housing choice pick up some of the above determinants, and could be improved. However, for most integrated land use –transport models the existing model of residential choice behaviour cannot be simply replaced by such more detailed simulation models, as they require a fundamentally different structure.

Finally, most integrated land use – transport models predict employment directly rather than focusing on locational choice behaviour of firms. To the extent that such behaviour is modelled, again the multinomial logit framework does not seem appropriate. Location choice of firms is often sequential, based on imperfect information, noncompensatory decision-making, a group decision rather than an individual decision, and often involves soft, non-spatial factors. Again, a different modelling approach would be required to incorporate such aspects.

Dream 3: Developing truly integrated models

Many so-called integrated land use –transport models involve some ad hoc combination of different modelling approaches. Often, the demand for different types of land use is determined by separate models, another set of models is used to allocate the demand across space. Next, this spatial distribution is used to predict traffic flows, using either a trip, tour or activity-based model, and a transportation model is finally used to calculate travel times. The notion of integration is often reduced to the principle that the calculated accessibility measures or travel times serve as one of the explanatory variables of the residential choice module.

- However, the literature on residential choice behaviour (e.g. Molin and Timmermans, 2003) has systematically shown that accessibility at best plays a marginal role in the residential choice decision. The attributes of the house and the physical and social characteristics of the neighbourhood are far more important. Although there is some literature in the field of transportation (e.g., Gayda, 1998; Kaysi and Abed, 1999; Cooper *et al*, 2002; Walker, *et al*, 2002) arguing the importance of accessibility, these studies have typically left out many critical housing attributes. Hence, it is not a surprise that they found significant transportation attributes. These effects are however likely statistical artefacts rather than evidence of behaviourally important constructs.

Other aspects of integration seem to receive far less attention, but might be more important to model today's cities. Examples are task allocation within households, the residential choice, job choice and vehicle holding decision for double-earner households, the scheduling of activities in time and space, competition and agglomeration of land uses/actors in the urban development process, the co-evolutionary development of demographics, employment sectors, land use and activity profiles, and a fuller treatment of varying time horizons, including both anticipatory and reactive behaviour, to name a few.

Dream 4: Modelling spatial planning

Most integrated transport – land use models do not explicitly take into account the role of spatial planning in urban development. However, dependent upon the country of interest, planners play an important role in shaping future cities. They can influence the process by developing general concepts that serve as new ideas or principles of development. They can restrict development in certain areas and stimulate development in others. They can also play an active role in investing in land development, housing, infrastructure, etc.

It is not readily evident how the spatial planning process should be modelled. Some planning concepts and objectives differ by political party and perhaps should be modelled in terms of the political parties who will be in power over some time horizon. Some planning concepts seem to have a short life cycle and therefore are difficult to model. On the other hand, the planning – building cycle in many countries often takes 10-15 years, and hence, one could simply incorporate what is already in the pipeline.

In any case, there seems to be a general shift from centralized planning to decentralised, incremental planning involving public private partnerships. Whatever model is used, it should try to mimic these tendencies.

6. Conclusions: some remaining fundamental dilemmas

In this paper, we have briefly review developments in complex, integrated models of land use – transport. To stimulate the discussion, we have taken the position that although progress has been made in terms of more detailed classifications and finer scales of spatial resolution, not much theoretical progress has been made. Especially the operational models are still largely based on traditional location theories and models that may have been adequate to describe traditional cities and traditional centralized planning methods, but that seem inadequate to describe the evolution of modern cities, dominated by service industries and information technology. Many theories depart from our knowledge about the evolution of urban systems evolve and the dynamic forces that shape them.

To revive integrated land use – transport models, we have identified a few central issues and dreamt that these issues could be solved. However, in that case, the field of modelling complex land use – transport systems will be left by some fundamental dilemmas. The field has consistently been criticized for its complexity and black box character. It seems however that a simplification of the approach will be counterintuitive. Any valid model should represent the key complexity of the phenomenon under investigation. The plea for behaviourally better models implies further complexity and many people will therefore continue to argue that the models are black boxes. There does not seem an easy solution to this dilemma.

Even in that case, however, it does not seem realistic to expect that any integrated model of land use – transport with the relative lack of data, can provide accurate land use forecasts at the level of individual cells. We should adjust our expectations and claims. Perhaps, provided behaviourally sound models will be developed and applied, we can claim that such models provide some rough possible qualitative indication for wider areas rather than a detailed quantitative assessment of tendencies and likely impact of land use and transport policy scenarios. The potential of these models is perhaps in the area of policy scenario development in the sense that they provide a platform for discussion as opposed to being accurate forecasting tools.

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