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Equilibrium v. dynamics in urban modelling

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Abstract

Urban modelling, traditionally dominated by static equilibrium formulations, has recently seen the emergence of models explicitly addressing the dynamics of urban change. Equilibrium models assume that urban land use and transport converge to equilibrium between supply and demand and focus on comparative static analysis of these equilibria. Dynamic models consider the different speeds of processes of urban change and concentrate on their outcomes over time and the path dependence this implies. It is becoming more and more apparent that without understanding the inherent inertia of different subsystems of cities it is impossible to assess their likely responses to land use or transport policies. For instance, it takes many years between decisions to invest in transport projects and their impact on mobility and location decisions of households and firms. Land use policies, such as development constraints, show their effects only after many years, as building stocks of cities change only incrementally. Relocations of households and firms within existing buildings respond to changes only gradually, as moves require substantial transaction costs. With new challenges from energy scarcity and climate change the time horizon of urban planning is extending beyond the present generation; this makes a long-term perspective of urban models even more important. The paper starts with a classification of urban change processes by speed of adjustment and shows how equilibrium models fail to deal with them. It discusses options of modelling dynamics and argues for recursive or quasi-dynamics as a rational trade-off between theory and operationality in spatially disaggregate urban models. It illustrates this by comparing how three existing recursive or quasi-dynamic urban models address temporal dynamics and points to applications of the three models in which the consideration of dynamics significantly added to understanding relevant policy issues.

1 Introduction

Today's cities are the result of the efforts of many generations. Even in periods of rapid growth, the total building stock of cities does not usually change by more than one or two percent per year. However, there are more rapid changes in the way the buildings are utilised. Even more rapid changes occur in the spatial interactions between activities.

These different time scales of urban change have long attracted the attention of urban historians, theorists and planners. Geddes (1915) borrowed the Darwinist paradigm of evolution to call for a deeper understanding of urban development. Urban historians like Mumford (1938; 1961) and Gutkind (1964-1972) aimed at understanding the growth and decline of cities as constellations of causes and effects. The Chicago school of urban sociologists, based on an evolutionist thoughts from philosophy (Spencer) and biology (Darwin), interpreted the city as a multi-species ecosystem, in which social and economic groups fight for survival (Park, 1936). The urban ecology school developed descriptors of spatio-temporal change in cities such as expansion, contraction, dispersion, invasion, succession and segregation and proposed qualitative theories of urban development, such as the concentric (Burgess, 1925), sector (Hoyt, 1939) or polycentric (Harris and Ullman,1945) theories of urban growth.

However, despite their spatial labels, these theories were essentially social theories. Space and time were included in them only in categorical terms, since analytical methods for treating intervals in space and time were only rudimentarily developed. Moreover, all urban ecology theories were in effect anti-evolutionist in that they assumed, in a questionable analogy to biological systems, an inherent tendency of social systems to converge to a stable equilibrium.

From then on, urban theory like most of the emerging regional science became more and more preoccupied with space and less with time. Location theory, in particular land-use rent theory (Alonso, 1964), was almost exclusively based on notions of accessibility and equilibrium of supply and demand and completely lost sight of the adjustment processes necessary to achieve that equilibrium. The Lowry (1964) model successfully stripped this theory of its last behavioural, i.e., economic, content, leaving physical distance as the one and only explanatory variable of the distribution of activities in space.

This voluntarily narrowing down in scope of urban theory is remarkable as it contrasted with the interest in temporal patterns taken by related disciplines. Since Schumpeter (1939), economists have tried to explain why economies seem to develop in cycles or wave-like patterns. It was apparent that these waves were reflected in the growth pattern of cities (Blumenfeld, 1954; Korcelli, 1970; Gottlieb, 1976). Non-equilibrium dynamic spatial theories encompassing cumulative or positive feedback effects (Myrdal, 1957; Hägerstrand,1966) challenged the neo-classical location theory. Suggestions were made for explicitly addressing the temporal dimension of social phenomena in a spatio-temporal framework (Hägerstrand, 1970; Isard, 1970).

All of these ideas remained without effect on urban theory and model building. Attempts to reconstruct the urban fabric from the daily space-time protocol of activities of individuals (Chapin and Weiss, 1968) had no followers. Forrester's dynamic urban model (1969) was denounced for its lack of spatial dimension and empirical content, but there were only few efforts to explore the potential of his method (Batty, 1971). Instead, mainstream urban theory-building and modelling adopted the most restricted engineering perception of the urban system as a system of movements as represented by the spatial interaction or Lowry model. This model, after nearly half a century of refinement (Wilson, 1967; 1970; 1974; Batty, 1976) and generalisation (Leonardi, 1981; Wilson, 1981; Clarke and Wilson, 1981; Anas, 1983), is essentially still the atemporal equilibrium model it was originally.

In particular the spatial interaction paradigm itself (the myth that workers choose their place of residence on their way home from work) turned out to be a veritable strait jacket which forces things together that clearly should be analysed separately, i.e., the decision to move, to choose a job, to make trips, etc., although of course these are interrelated, but only in a lagged and indirect way.

This paper argues that without understanding the inherent inertia of different subsystems of cities it is impossible to assess their likely responses to land use or transport policies. For instance, it takes many years between the completion of transport projects and their impacts on mobility and location decisions of households and firms. Land use policies show their effects only after a long time as building stocks change only incrementally. Relocations of households and firms respond to changes only gradually as moves require substantial transaction costs. New challenges of energy scarcity and climate change extend the time horizon of urban planning and make it even more important when policy impacts will arise. The recent global recession is perhaps the best example of the importance of understanding disequilibria.

The paper starts with a classification of urban change processes by speed of adjustment and shows how equilibrium models fail to deal with them. It discusses options of modelling dynamics and argues for quasi- or recursive dynamics as a rational trade-off between theory and operationality in spatially disaggregate urban models. It illustrates this by comparing how three existing dynamic urban models address temporal dynamics and deal with feedback effects to produce results that capture the key features of urban dynamics, such as price responses and their interaction with demand and supply choices, and points to applications of the three models in which the consideration of dynamics significantly added to understanding relevant policy issues.

2 URBAN CHANGE PROCESSES

In this section, urban change processes relevant for urban policy making and planning are reviewed with particular attention being paid to their temporal characteristics. For this a set of descriptive dimensions of urban change processes has been developed based on a stimulus-response scheme. The first dimension identifies the stimulus itself, the “driver” of change. The second identifies which stock is affected by the change – note that implicit in this is a category of “actors”, such as industrial firms or households, who make the decisions in response to the stimulus which appear as the change in this particular stock. The remaining four dimensions characterise the kind of response effected on the stock by the stimulus. The response time indicates the time normally elapsing between the stimulus and the first sign of response. The response duration indicates the time normally elapsing between the first sign of response and its end, i.e., the time needed for the response to work its way through the stock. This time may also be called the lifecycle of the stock. The response level is related to the response duration. It indicates the normal rate of change associated with the process in relation to the magnitude of the affected stock. If the lifecycle of the stock is a long one, the rate of change will be small, and vice versa. The last dimension, response reversibility, indicates the degree to which the process may reverse its direction. Table 1 shows these dimensions for the direct responses of selected urban change processes organised in six levels of different response time, duration and level. The characteristics described relate to highly developed economies; less developed economies, especially those with less elaborate planning systems and more informal development, may show different rates of response and different levels of reversibility.

Table 1. Urban change processes (developed from Wegener et al., 1986)

Speed	Change process	Stock affected	Response time (years)	Response duration (years)	Response level	Reversibility
very slow	transport construction	transport networks	5-10	>100	low	hardly reversible
	land use change	land use pattern	5-10	>100	low	hardly reversible
slow	industrial construction	industrial buildings	3-5	50-100	low	very low
	residential construction	residential buildings	2-3	60-80	low	low
medium speed	economic change	employment/ firms	2-5	10-20	medium	reversible
	demographic change	population/ households	0-70	0-70	low/high	partly reversible
fast	firm relocation	workplace occupancy	<1	5-10	high	reversible
	residential mobility	housing occupancy	<1	5-10	high	reversible
very fast	change in demand	goods transport	<1	<5	high	reversible
	change in mobility	person travel	<1	<1	high	reversible

Figure 1 illustrates this view of urban systems distinguishing eight urban subsystems by their speed of change: very slow (networks, land use), slow (workplaces, housing), medium speed (employment, population), fast (workplace and housing occupancy) and very fast (goods transport and travel). There is a ninth subsystem, the urban environment that is subject to all these speeds of urban change.

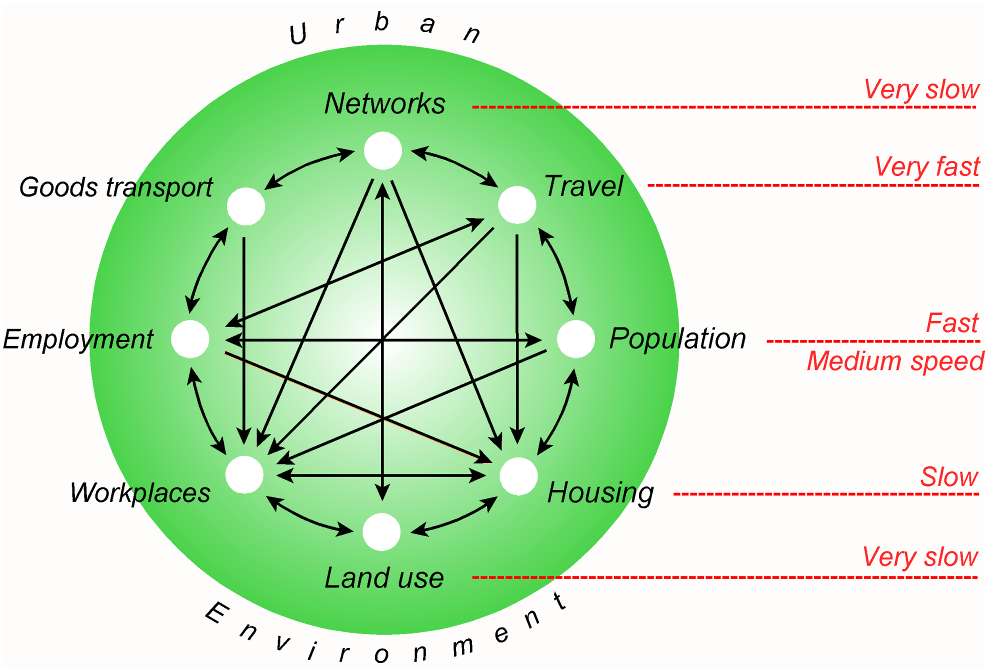

Figure 1. Urban subsystems by speed of change

Very slow processes: transport and land use

Rome was not built in a day. Europeans still travel on Roman roads. Human settlements evolve over a long time span by the cumulative efforts of many generations. The resulting physical structure of cities displays a remarkable stability over time prevailing even after major devastations such as wars, earthquakes, or fires, and changing only in relatively small increments in normal times.

Major transport investments tend to be the most durable and also involve the longest time lags between planning and completion. The same is true for the appropriation of open space for human settlements. The common feature of these changes is their virtual irreversibility. This becomes apparent if one looks at sequences of historical maps showing different phases of city growth; even in modern aerial photographs it is normally easy to detect physical patterns that have not changed for centuries, although the city may have been destroyed and rebuilt several times. This irreversibility is mainly due to the heavy investment contained in transport infrastructure like canals, railways and major thoroughfares. Another factor of rigidity is the system of property rights, in particular the separation of public and private land, which makes it very difficult to establish totally new patterns of rights-of-way and land use.

Slow processes: construction

In comparison to transport lines and land use patterns, buildings are less permanent, because they may be replaced or converted to other uses by private decisions; but since they represent substantial investments, demolition and conversions affect only a minimal percentage of buildings each year, even in relatively young cities of North America.

Industrial construction is concerned with capital-intensive installations having an average lifetime of well over fifty years. Planning and construction of industrial plants and office buildings including applications for building permits and land development may take several years, hence a delay of between three and five years from the first decision to invest and completion of the building is not uncommon. Similar, but somewhat lesser, delays are normally associated with residential buildings, which also have a slightly shorter lifetime. The long lifetimes of the physical stock is reflected in the low rates of change: if reconstruction after wars and natural disasters is discounted, annual replacement amounts to only between one and two percent of the existing stock.

Medium-speed processes: economic and social change

Underneath this major current of urban change there are more rapid fluctuations or cycles affecting various aspects of the urban fabric such as the economy or the social composition of the population. They result in subtle shifts or fundamental transitions in the way the physical structure of cities is utilised, and these changes are visible only on a medium-term scale.

The most significant kind of economic change are changes of the number and sectoral composition of employment. These changes primarily reflect the secular transition of the production system from primary and secondary to tertiary and quaternary industries caused by technological innovation and changing consumption patterns. They also reflect world-wide cycles of prosperity and recession, exports and imports, resources and prices. In general, the regional economic system tries to respond immediately to exogenously imposed economic change, but frictions on the labour market (in the growth case) or union power and government controls (in the recession case) delay this adjustment process. The lifetime of employment location decisions is related to the average lifecycle of a firm, which is in the range of between 10 and 15 years. Hence the impact of economic growth or decline on the employment of an industry is rather direct and normally reversible.

Demographic changes comprise a variety of changes of population and households; hence there is a large variation in response time and duration within this group of changes. Birth, aging and death, marriage, cohabitation and separation affect the number and age distribution of the population as well as households. These changes are normally treated as exogenously determined and thus have no explicit response time. Their impact on the total number of population and households is small, but spread out over a long duration due to the long lifetime of individuals and households.

Fast Processes: firm relocations and residential mobility

Finally there are even more rapid phenomena of urban change that are planned and completed in less than a year's time. They refer to the relocations of workplaces and households within given buildings and communication facilities. Small firms relocate into vacant building space, workers decide to accept a vacant job more conveniently located to their place of residence, households move into vacant dwellings. These types of mobility involve substantial costs and effort and are therefore normally undertaken only every five or more years. They do not change the physical structure of the city nor the distribution of activities but the composition of vacant and occupied stock, i.e. workplace and housing occupancy, and they are reversible.

Very fast changes: goods transport and travel

In contrast to this, daily deliveries or person trips have no impact on the distributions of workplaces and population in the urban system because they start and end at the same place. So they are clearly subordinate to relocation decisions in the short term, although in the long term they play an important role for relocation decisions through the accessibility they generate. Due to this linkage, daily trips, especially work trips, have an ambiguous temporal structure. Seen as a short-term phenomenon, they are planned and completed within hours. Seen in a longer time frame, they form habitual patterns that do not change much faster than workplace and household locations. Daily movements are reversible.

3 MODELS OF URBAN CHANGE

What are the implications of these differential rates of change in urban processes for the construction of urban models? The most fundamental one is that urban change processes are slow in relation to human life and planning perspectives, and that therefore urban models intended for planning should take account of the retarding forces, frictions, and delays responsible for that inertia. A second implication is that there are different levels of change with different temporal characteristics, and that these levels interact and that therefore models of urban change should distinguish between fast and slow change processes and explicitly recognise their different levels of responsiveness, duration, impact, and reversibility. Most existing urban models do not pay the requisite attention to the hierarchy of temporal scales of urban change.

This section looks briefly at how the temporal scales of change are handled in two representative classes of urban models and their treatment of time: static equilibrium models and dynamic models.

Static Equilibrium models

Equilibrium models are based on the assumption that interdependent model variables, such as prices, supply and demand, adjust to equilibrium instantaneously and with no path-dependence. Time is abstracted out of the model: they do not represent chronological time. There are only few urban models determining a general equilibrium of transport and land use with endogenous prices (e.g. Anas and Liu, 2007). Other models are equilibrium models of transport only or of transport and activity location separately.

The majority of urban models to date are equilibrium models. The most prominent urban equilibrium model is the ubiquitous spatial interaction model. Used as a transport model, it predicts transport flows in equilibrium at a particular point in time. Used as a location model as in the Lowry model it predicts an equilibrium combination of locations and flows at a particular point in time. This is also true for multiregional input-output models, such as MEPLAN (Echenique et al., 1969; 1990), TRANUS (de la Barra, 1979, 1989) and PECAS (Hunt and Abraham, 2005) in which origins and destinations of commodity and passenger flows are derived from an intersectoral input-output table, with households defined as sectors producing labour and consuming commodities, and flow distribution and model split are derived from a network-based spatial interaction model. The most disturbing feature of these models is that they have no memory but distribute activities in each period from scratch: the *instant metropolis*.

Obviously, no considerations of time enter the rationale of spatial interaction models. Rather, they weld together change processes with totally different time behaviour: medium-speed changes of activities and fast daily movements. In fact spatial interaction location models predict a relatively slow and inert process, location, from a volatile and flexible process, travel. However, in the real world, daily travel decisions are clearly subordinate to location decisions. Of course, accessibility is relevant for location, but only in a highly aggregate, lagged and indirect way, as one location factor among others.

Dynamic models

In contrast to static equilibrium models that abstract away time and focus on a comparison of hypothetical equilibria, dynamic models make the representation of movement through time explicit. Early efforts to model spatial dynamics of cities treated time as continuum (Harris and Wilson, 1978; Beaumont et al., 1981; Allen et al., 1981). However, today the most common form of temporal representation in dynamic urban models is through recursive or quasi-dynamic models in which the end state of one time period, usually in time steps of one year, serves as the initial state of the subsequent one.

There are several operational urban models today which take advantage of this possibility as a rational trade-off between theory and operationality in spatially disaggregate urban models, including the three models presented in the following section. These models typically operate with a combination of differently constructed submodels for different subsystems or change processes. Such composite models have the advantage of much more flexibility in the selection of variables, relationships, and modelling techniques, but they have to solve the additional problem of consistently exchanging information between the submodels, and it is here where time considerations become critical.

Normally, in composite models, submodels are processed sequentially. This creates problems of consistency (e.g., when migrants entering the region at mid-period are to be merged with the existing population) or of plausibility (e.g., when two simultaneous, continuous, and interlinked processes, like household formation and housing search, have to be modelled separately). More serious problems arise when submodels are connected by important two-way feedback links or operate on the same variables (e.g. household formation and labour mobility, housing demand and housing supply, housing construction and land development). In this case the decision in which sequence the submodels are to be executed may be important. To decide that submodel A is to precede submodel B means that A has priority access to scarce resources like land but will not know what is going on in B before the next simulation period. Conversely, B may get less of the scarce resources but can utilise its knowledge of the results of A immediately. Some of these problems can be reduced by iteratively processing blocks of submodels several times during a simulation period. Whatever submodel sequence is chosen decides on the implicit lag structure of the model.

The implicit lag of a recursive model is equal to the duration of its simulation period, because that is the time elapsing before changes generated in the model are perceived. However, shorter implicit lags are introduced if during a simulation period submodels are executed sequentially, i.e., later submodels operate on variables processed by earlier ones. On the other hand, iteration or other kinds of equilibration between submodels during a simulation period assume zero time delays between subsystems.

The modeller may override implicit lags through explicit delays and may specify their time characteristics, i.e., time-discounting, such as exponential or others. Various possibilities of working with delays have been demonstrated by Forrester (1961; 1969). Following Forrester, delays are essential for understanding complex systems, and this is in line with the path dependency assertion of bifurcation theory, that already small changes in the constellation of system variables can lead to significantly different paths of system behaviour.

What are the conclusions for the choice of a period length for urban change models? Again citing Forrester, the simulation period should be short enough not to influence the behaviour of the model; in particular it should not be used to introduce implicit lags. As a rule of thumb, Forrester suggests that the period length should be half or less of the shortest relevant delay present in the system. Following this rule, most current urban models with period lengths of five or more years are inadequate to capture the dynamics of urban change. For that a period length of one year should be considered the maximum if only slow and medium-speed processes are to be modelled. An even shorter period length is required if also very fast changes are of interest.

4 Examples

This section compares how three existing recursive or quasi-dynamic urban models address temporal dynamics and deal with feedback effects to produce results that capture the key features of urban dynamics, such as price responses and their interaction with demand and supply choices.

IRPUD

The IRPUD model is a simulation model of intraregional location and mobility decisions in a metropolitan area (Wegener, 1982; 1983; 2001). It receives its spatial dimension by the subdivision of the study area into *zones* connected with each other by transport networks containing the most important links of the public transport and road networks coded as an integrated, multimodal network including all past and future network changes. It receives its temporal dimension by the subdivision of time into *periods* of one or more years' duration. The model predicts for each simulation period intraregional location decisions of industry, residential developers and households, the resulting migration and travel patterns, construction activity and land-use development and the impacts of public policies in the fields of industrial development, housing, public facilities and transport.

The IRPUD model has a modular structure and consists of six interlinked submodels operating in a recursive fashion on a common spatio-temporal database:

(1) The *Transport Submodel* calculates work, shopping, social and education trips for four socioeconomic groups and three modes, walking/cycling, public transport and car. It determines a user-optimum set of flows where car ownership, trip rates and destination, mode and route choice are in equilibrium subject to road congestion.

(2) The *Ageing Submodel* computes all changes of the stock variables of the model which are assumed to result from biological, technological or long-term socioeconomic trends originating outside the model (i.e. which are not treated as decision-based). These changes are effected in the model by probabilistic ageing or updating models of the Markov type with dynamic transition rates. There are three such models, for employment, population and households/housing.

(3) The *Public Programmes Submodel* processes a large variety of public programmes specified by the model user in the fields of employment, housing, health, welfare, education, recreation and transport.

(4) The *Private Construction Submodel* considers investment and location decisions of private developers, i.e. of enterprises erecting new industrial or commercial buildings, and of residential developers who build flats or houses for sale or rent or for their own use. Thus the submodel is a model of the regional land and construction market.

(5) The *Labour Market Submodel* models intraregional labour mobility as decisions of workers to change their job location in the regional labour market.

(6) The *Housing Market Submodel* simulates intraregional migration decisions of households as search processes in the regional housing market. Housing search is modelled in a stochastic microsimulation framework. The results of the Housing Market Submodel are intraregional migration flows by household category between housing by category in the zones.

Only the Transport Submodel is an equilibrium model referring to a *point in time*. All other submodels are incremental and refer to a *period of time*. Submodels (2) to (6) are executed once in each simulation period, while the Transport Submodel (1) is processed at the beginning and the end of each simulation period. Each submodel passes information to the next in the same period and to its own next iteration in the following period. Construction projects started in the *Public Programmes* and *Private Construction* submodels are released to the market only after a number of years.

The IRPUD model has been applied in several projects to analyse the likely impacts of integrated land use and transport policies in the urban region of Dortmund, Germany, such as the EU projects *PROPOLIS: Planning and Research of Policies for Land Use and Transport for Increasing Urban Sustainability* (Lautso et al., 2004) and *STEPs: Transport Strategies under the Scarcity of Energy Supply* (Fiorello et al., 2006).

DELTA

DELTA is a modelling package developed since 1995. One of its original objectives (Simmonds, 1999) was to provide a practical modelling tool based on a quasi-dynamic modelling approach, for the reasons discussed above. We note here the main components of a full application with particularly reference to their dynamics. DELTA models are linked to external transport models which take in land use data and return generalised costs and environmental indicators.

The DELTA model contains ten submodels:

(1) The *Accessibility* submodel uses output from the transport and land-use models to calculate accessibility measures such as the ease of reaching different kinds of work and shopping opportunities or of being reached by a potential workforce. These are converted into measures of accessibility for each type of household and of employment.

Measures of area accessibility to markets and suppliers for economic sectors are also calculated. All of these measures are in themselves static.

(2) The *Development* submodel forecasts new floorspace to be built in each zone starting in the current year. This is controlled by planning policy inputs and strongly influenced by previous rents and densities. Development takes one or more years to complete.

(3) The *Transition* submodel implements demographic changes and, inter alia, calculates new households which must locate, households who may locate and those are immobile in the current year.

(4) The *Investment* component of the Economic submodel forecasts changes in the distribution of productive capacity. The default distribution of investment is in proportion to previous capacity; an area’s share of a sector’s total investment increases if its accessibility to markets is improving and its costs are decreasing. Changes in accessibilities and costs are measured over the previous decade.

(5) The *Production* submodel is a spatial input-output model, limited to modelling the faster- changing distribution of economic exchanges given the slower changes in capacity and the variously-changing locations of the demands for each sector.

(6) The *Migration* submodel forecasts the longer-distance moves of households between areas, in response to the conditions in the previous year, and with coefficients reflecting the general reluctance of many households to making such moves.

(7) The *Car-ownership* submodel models forecasts probabilities of car-ownership, using one-year lagged employment and income per household by zone and type.

(8) The *Household Location* and *Employment Location* submodels locate the households and jobs which are “mobile” in the current year. These again modify previous distributions in response to changes. Influences for households are housing supply, accessibility, cost of location, etc, all of which are endogenous to the model. Changes are measured over a number of years which varies according to the household type.

(9) The *Employment Status and Commuting* submodel models whether-to-work and where-to-work for household members given their locations and the locations of jobs.

(10) The *Housing Quality* submodel models the evolution of the existing housing stock. Housing occupied by high-income households tends to be gradually improved; low incomes and vacancy lead to gradual decline.

All ten model components are repeated in turn, once for each year, until the next transport model year – at which point DELTA provides the appropriate land-use inputs to the transport model, waits for it to run, and then continues from (1). The system as a whole shows quite complex dynamics with a strong element of cumulative causation over time.

Current applications of DELTA with all these components include those for Strathclyde (Aramu et al., 2006), Scotland (Bosredon et al, 2009), Greater Manchester (Dobson et al., 2009) and London (Feldman et al., forthcoming).

UrbanSim

UrbanSim was initially created in the mid-1990s as a dynamic microsimulation model system to be coupled with existing travel model systems to support the analysis of the effects of transportation system investments on medium term household and employment location choices and on longer-term real estate development patterns (Waddell, 2002, UrbanSim, 2011).

The basic structure of UrbanSim shares a similar approach to IRPUD and DELTA in the use of a sequence of models run annually, and the interfacing of travel modelling in specified years. It is a pure microsimulation model in the sense of using no aggregation of agents. Individual households, persons, businesses and/or jobs are represented with full enumeration. The treatment of geography is flexible, and models have been applied using grid cells, zones, and parcels. This flexibility is a general advantage of microsimulation modelling, particularly if such flexibility is emphasised in the software implementation.

The UrbanSim model system contains a core set of models, which can be interactively created and configured in the user interface using model templates for a range of model types (choice, regression, allocation, etc.). The simplest model applications might contain only a small subset of these models, while other applications contain additional models representing processes such as household evolution, demand for water, or land cover change. The list below is from the application of UrbanSim to the Puget Sound region surrounding Seattle, Washington:

(1) The *Real Estate Price* submodel predicts prices of parcels using a hedonic regression model.

(2) The *Expected Sale Price* submodel predicts prices of possible real estate proposals using a hedonic regression model.

(3) The *Development Proposal Choice* submodel: chooses real estate proposals to be built (including redevelopment) using weighted random sampling based on a predicted return on investment (ROI).

(4) The *Building Construction* submodel demolishes buildings (for redevelopment) and builds new buildings according to the chosen proposals.

(5) The *Household transition* submodel creates and removes households and updates the set of persons accordingly based on random sampling and is driven by macroeconomic predictions.

(6) *Employment Transition* submodel creates and removes jobs using random sampling and is driven by macroeconomic predictions.

(7) The *Household Relocation Choice* submodel determines households for moving using a logit model.

(8) The *Household Location Choice* submodel locates moving households into buildings using a multinomial logit model.

(9) The *Employment Relocation* submodel determines jobs for moving using weighted random sampling.

(10) The *Employment Location Choice* submodel locates moving jobs into buildings using a multinomial logit model.

(11) The *Work at Home Choice* submodel simulates workers decision to work at home or out of home based on a logit model.

(12) The *Workplace relocation choice* submodel simulates workers decision to change jobs based on a logit model.

(13) The *Workplace Choice* submodel assigns individual jobs to workers using a multinomial logit model with sampling alternatives.

The *Travel Model Interface* is not a model per se, but interfaces with a travel model to pass information to the travel model on the spatial distribution of agents (jobs and households) and to retrieve from the travel model updated travel impedances such as time, generalised cost, or logsums from a mode and destination choice model. These measures are used in several of the UrbanSim models.

UrbanSim makes heavy use of discrete choice models to represent behaviour such as household and business location choices and real estate development. The software system includes model specification and maximum likelihood estimation algorithms to internalise these functions. A novel methodology has been implemented for calibrating the uncertainty in model predictions using a statistical approach known as Bayesian Melding (Sevcikova et al., 2007).

UrbanSim has been widely adopted for use by Metropolitan Planning Organisations in the United States for operational use in regional transportation planning, in spite of numerous technical and political challenges in integrating land use and transportation planning and modelling (Waddell, 2011). UrbanSim is being used in projects in North America, Europe, Asia and Africa, and has been interfaced with most existing travel modelling platforms, including activity-based frameworks that have emerged in recent years. The implementation of UrbanSim is within an open source software platform called the Open Platform for Urban Simulation (OPUS).

The most current activity on the UrbanSim model system is to simulate the evolution of urban geometry. By modelling the topological structure and spatial patterns and relationships among buildings, parcels, blocks, and streets, the project has begun to model the processes of subdivision of land and creation of internal streets for housing development, and the consolidation and redevelopment of parcels in built-up urban areas, with explicit updating of the associated geometries. This process lends itself to 3D visualisation of buildings, and the explicit modelling of real estate decisions that include proforma analysis of the profitability of alternative development options (Vanegas et al, 2009).

5 CONCLUSIONS

The intention of this paper has been to point to a neglected dimension of urban modelling research, time. Starting from a reflection on the different levels of awareness of the importance of time in the history of urban theory, it has attempted to demonstrate that even the most recent efforts to capture time in dynamic urban models still have some way to go to become models of urban evolution. In the meantime, it argues, quasi-dynamic recursive models composed of subsystem-specific submodels with implicit and explicit time delays are preferable to equilibrium models and represent a rational trade-off between theory and operationality.

The attraction of equilibrium as a concept is clear: it admits simple comparisons in an analytically elegant way. Unfortunately, urban regions are much more complex in their spatial patterns and temporal dynamics than can be represented in static equilibrium frameworks. While much remains to be done in further refining the dynamic approach to modelling urban regions, there is considerable evidence from the development and application of such models that they can both represent the essential dynamics of urban areas as reflected in longitudinal validation of such models, and that they can be used for applied policy analysis and planning. Urban regions are not static and should not be represented as such.

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