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THE TIME SCALE OF URBAN CHANGE

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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, changing only in small increments in normal times. However, underneath this major current of urban change there are more rapid fluctuations or cycles affecting the way the physical structure is utilized. Most existing urban models do not pay the requisite attention to the different time scales of urban change. An outline of an urban model being multilevel in its temporal dimension is sketched.

INTRODUCTION

> "Evolution is most plainly, swiftly in progress, most manifest, yet most mysterious. ... The patterns here seem simple, there intricate, often mazy beyond our unravelling, and all well-nigh are changing, even day by day, as we watch."
>
> Patrick Geddes, Cities in Evolution, 1915

In his famous treatise on town planning, Patrick Geddes borrowed the Darwinist paradigm of evolution to support his appeal for a deeper understanding of the nature of cities. The study of urban evolution for him comprised three elements: inquiry into the past ("Whence?"), analysis of present processes("How?"), and foreseeing and preparing for tomorrow ("Whither?"). This rational view of urban planning might have been the starting point for a new urban science, but it was premature. Even where planners followed Geddes' prescription "Survey before plan!", the surveys normally remained cross-sectional tabulations or maps and bore no relation to the plans designed thereafter.

The study of the urban past remained the domain of urban historians like Mumford (1938; 1961) and Gutkind (1964-1972). Their method was essentially hermeneutic, i.e., aimed at understanding individual processes as unique constellations of specific causes and effects. Beyond the observation of similarities in different places at different times, nor regularities or law-like covariations of variables were sought.

This changed when between the wars the Chicago school of urban sociologists looked closer into social change processes on the neighbourhood and urban levels. Based on an adaptation of evolutionist thoughts from philosophy (Spencer) and biology (Darwin), they interpreted the city as a multi-species ecosystem, in which social and economic groups fight for survival (Park, 1936). The urban ecology school developed a set of macro-descriptors of spatio-temporal social change in cities such as expansion, contraction, dispersion, invasion, succession, segregation, or dominance. These concepts were empirically testable and could be used for generalisations and theory-building. Consequently, a number of qualitative theories of urban development were put forth such as the concentric (Burgess, 1925), sector (Hoyt, 1939), or polycentric (Harris and Ullman, 1945) theories of city 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; Pred, 1966; Korcelli, 1970; Gottlieb, 1976). Non-equilibrium dynamic spatial theories encompassing cumulative or positive feedback effects (Myrdal, 1957; Hägerstrand, 1966) challenged the neoclassical 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 while overcoming its deficiencies (Batty, 1971). Instead, the mainstream of urban theory-building and modelling completely 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 some twenty years of refinement (Wilson, 1967; 1970; 1974; Batty, 1976) and generalization (Williams and Senior, 1978; Coelho and Williams, 1978; Leonardi, 1981; Anas, 1983), is essentially still the atemporal equilibrium model it used to be and with each advance in mathematical rigour and elegance seems to get farther away from reality.

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 analyzed 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. Moreover, there are no people in this paradigm, no households, no entrepreneurs, no landlords, no developers; there are no distorted perceptions, no incomplete information, no uncertainty, no biases, no heuristics, no adaptation, no learning. There are no real change processes, no construction, no upgrading, no demolition, no real supply and demand variables, no rents and land prices, no interaction between supply and demand, no markets, no market distortions such as oligopolies, price controls, legal constraints, public interventions.

Some of these issues have been taken up by more recent approaches. Their common characteristic is their interest in dynamics. This rediscovery of time was partly motivated by new results in the biosciences with respect to the behaviour of complex ecosystems, partly by the availability of new mathematical instruments like catastrophe and bifurcation theory. However, the present attempts to apply these new concepts and tools to urban systems still leave many questions unanswered.

In this paper, some of these questions will be asked. In particular, the claim of these models to capture the dynamics of evolutionary processes in urban systems will be examined. To this purpose, the paper proceeds, after this introduction, with a synopsis of urban change processes thought to be relevant with particular reference to their temporal characteristics. Then current modelling approaches are evaluated as to their ability to address the dynamics of such processes. Finally the outline of an urban model is sketched that may treat the temporal structure of urban change processes more effectively than other models by being multilevel in its temporal dimension.

URBAN CHANGE PROCESSES

In this section, various kinds of urban change processes that may be considered relevant for urban policy making and planning are reviewed with particular attention being paid to their temporal characteristics. Following Snickars et al. (1982), a distinction is made between long-term, medium-term, and short-term, or slow, medium-speed, and fast processes.

Before doing so, a few definitions need to be made. What is a fast process? One involving a high rate of change of the stock affected? One that starts, picks up momentum, and terminates quickly? One that occurs frequently? One that converges to an equilibrium quickly? None of these definitions alone seems sufficient. The first one is too dependent on how the stock is defined and may vary with different levels of aggregation. The second one addresses only changes in the rates of change, but not the rates themselves. The third definition does not distinguish anything because in a micro perspective nearly all urban processes occur in a tightly interwoven fabric of events. The last definition rules out processes that may not converge to an equilibrium.

Therefore, a set of descriptive dimensions of urban change processes have been developed based on a stimulus-response scheme. The first dimension identifies the process itself, or the stimulus. The second one identifies which stock is affected by the change. Four other dimensions characterize 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 life-cycle 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 life-cycle 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 the above dimensions summarized for selected urban change processes organized in three levels of different response time, duration, and level. They will be discussed below.

Table 1. Urban change processes

Level	Change Process	Stock Affected	Response Time (years)	Response Duration (years)	Response Level	Reversibility
1 Slow	industrial construction	industrial buildings	3-5	50-100	low	very low
	residential construction	residential buildings	2-3	60-80	low	low
	transport construction	transport system	5-10	>100	low	nearly irreversible
2 Medium Speed	economic change	employment/ unemployment	2-5	10-20	medium	reversible
	demographic change	population/ households	0-70	0-70	low/high	partly reversible
	technological change	transport equipment	3-5	10-15	medium	very low
3 Fast	labour mobility	workplace occupancy	<1	5-10	high	reversible
	residential mobility	housing occupancy	<1	5-10	high	reversible
	daily mobility	traffic	<1	2-5	high	reversible

Slow Processes (Level 1): Construction

Rome was not built in a day. 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 small increments in normal times.

The first three kinds of change of Table 1 illustrate this. Industrial construction is concerned with capital-intensive installations having an average lifetime of well over 50 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 3 and 5 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. However, major trans-port investments tend to be the most durable and also involve the longest time lags between planning and completion. The long lifetimes of the physical stock is reflected in the low rates of change: if reconstruction after the war is discounted, normal replacement amounts to only between one and two percent of the existing stock each year.

Another important feature of physical changes is their virtual irreversibility. This becomes apparent if one looks at sequences of historical maps showing different phases of city growth; even in aerial photographs taken at one point in time 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 lines like canals, rails, or 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. In comparison, buildings may be called less permanent, because they may be replaced or converted to other uses by private decisions; but since they, too, represent substantial investments, demolition and conversions affect only a minimal percentage of buildings each year.

Medium-Speed Processes (Level 2): Economic, Social, Technological 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, the social composition of the population, or the communication systems. They result in subtle shifts or fundamental transitions in the way the physical structure of cities is utilized, and these changes are visible only on a medium-term scale. The three kinds of change in the middle section of Table 1 are examples of such changes.

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 normal lifetime of employment decisions equals the average life-cycle 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 affecting population and households, hence there is a large variation in response time and duration within this group of changes. A more detailed list of demographic changes is presented in Table 2. Birth, aging, and death affect the number and age distribution of 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.

This changes only if specific age groups or household types are inspected. For instance, with respect to primary school attendance, the response time of births is 6 years, and because children attend primary schools only for 4 years, the impact of changing birth rates on primary schools is substantial. Similar observations apply to other stages of the educational system or occupational affiliation. Another important group of changes are those that affect household formation. Such changes are marriage, divorce, or remarriage, or all cases in which a relative joins or separates from a household. These changes, too, have no apparent time lag from the perspective of the urban analyst, while their impact on the composition of households is high and increases with rising divorce rates, earlier separation of children from their parents' home, and the gradual disappearance of the three-generation family.

Still other changes refer to important household characteristics like nationality (naturalization) or socio-economic group (income changes), but these will not be discussed here. It will be observed that with increasing disaggregation change processes tend to become unidirectional and thus by definition irreversible.

Table 2. Demographic change processes

Level	Change Process	Stock Affected	Response Time (years	Response Duration (years)	Response Level	Reversibility
2 Medium Speed	birth/aging/ death	population/ households	–	0-170	low	irreversible
		primary schools	6	4	high	irreversible
		secondary schools	10	6-10	medium	irreversible
		universities	18	4-8	medium	irreversible
		economically active age	16-22	45-50	low	irreversible
	joins/leaves labour force	labour force	–	10-50	medium	reversible
	naturalization	population/ households	–	0-70	low	virtually irreversible
	marriage/ divorce	households	–	1-50	medium	reversible
	relative joins/leaves	households	–	1-50	medium	reversible
	change of income	households	–	1-50	medium	reversible

Technological change plays already a part as one of the motors of economic change, but itself has strong impacts on all aspects of urban life, in particular on transportation and communication. Technological innovations like new generations of automobiles, buses, underground cars, new schemes of public transport operation, or new telecommunication services are introduced within a few years and have a technical and economic lifespan of between 10 and 20 years. Hence the rates of transition of the affected systems are substantial. Technological change is in principle reversible, but historical examples of technological degradation are rare.

The common characteristic of the above medium-speed changes is that they do not affect the physical structure of the city, but only the way it is used. So medium-speed changes refer to activities and equipment.

Fast Processes (Level 3): 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 mobility of people, goods, and information within given buildings and communication facilities. These changes range from job relocations and moves to the daily pattern of trips and messages. They are the most volatile occurrences of urban change, but at the same time the most easily observable. The last three kinds of change in Table 1 are representative for this category.

A distinction has to be made between relocations and daily movements. Small firms relocate from one zone to another 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 every 5 or more years. They do not change the distribution of activities, but affect the composition of vacant and occupied stock, i.e., workplace and housing occupancy. In contrast to this, daily trips have no impacts at all on any distributions 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. Relocations and daily movements are fully reversible.

MODELS OF URBAN CHANGE

It is recognized that there is room for counter arguments about the categorization used in the above discussion. For a more thorough analysis, an empirical survey of urban change processes and their temporal characteristics would be desirable – it certainly would reveal some dispersion of values around the ranges suggested by Tables 1 and 2. However, even in the absence of such survey, some general conclusions can be drawn: change processes relevant for the spatial development of cities differ widely in terms of response time, duration, level of impact, and reversibility. Changes affecting the physical stock of the city (Level 1) have the longest response time and longest-lasting impacts, but occur only in small increments and are nearly irreversible Changes affecting the distribution of activities in the urban system (Level 2) have medium response times, and their impacts are less permanent and irreversible. The most rapid and short-lived changes are due to mobility processes of individuals, goods, and information within the urban system (Level 3).

What are the implications of this 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, medium-speed, and slow change processes and explicitly recognize their different levels of responsiveness, duration, impact, and reversibility.

It is the theme of this paper that most existing urban models do not pay the requisite attention to the hierarchy of temporal scales of urban change. This will be demonstrated by looking briefly at two representative classes of urban models and their treatment of time. Again, first a few definitions: A model is called dynamic as opposed to static if it has an explicit time dimension, if its inputs and outputs vary over time, and if its states depend on its earlier states. A rudimentary form of dynamic model is a comparative statics one which models the change between two states. A sequence of comparative statics models is called a recursive model; in a recursive model the end state of one time period serves as the initial state of the subsequent one. Following Batty (1976), a model is called quasi-dynamic, if it contains static parts in a dynamic framework.

Quasi-Dynamic Models

The majority of urban models to date are either static or quasi-dynamic. The most prominent static urban 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. Obviously, no considerations of time enter the rationale of this model. Rather, it welds together change processes with totally different time behaviour: medium-speed changes of activities (Level 2) and fast daily movements (Level 3). In fact the spatial interaction location model predicts 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 aggregated, lagged, and indirect way, and always as one location factor among others.

This arbitrary exchange of cause and effect may be the prime explanation for the poor predictions generally achieved with the production-constrained spatial interaction location model. Because the model ignores the inherent inertia of the physical stock, it postulates an equilibrium which never has the time to develop. To account for this basic misconception, in most applications of the Lowry model, severe zonal constraints have to be imposed in order to get reasonable results.

The situation gets worse if the model is applied for forecasting purposes, i.e., in a quasi-dynamic framework. Even if the predicted totals look acceptable when compared with observed totals, the forecasting errors with respect to the rates of change normally do not. But only the rates of change are of interest, because the totals are known, and the rates of change are usually very small compared with the totals. Many modellers have responded to this difficulty by applying the spatial interaction location model only to the increments of activities. However, this approach makes separate models for updating the existing stock necessary: aging and household formation submodels in the case of population, and vintage submodels in the case of industrial and residential buildings, and this creates problems of subsystem linkage.

Problems of subsystem linkage arise when different, but interrelated processes are modelled together, e.g., aging and relocation (as above), basic and service employment (in the Lowry model), activities and transport (in land-use/transport models), or supply and demand (in housing or labour market models).

Some of these relationships can be formulated as constraints of one process on the other and thus be embedded in the original spatial interaction framework. This has been a field of significant accomplishments for some years (Boyce, 1977; Los, 1978, Coelho and Williams, 1978; Brotchie et al., 1980; Sharpe and Karlqvist, 1980; Leonardi, 1981). These efforts are directed at retaining the spatial interaction model through generalization, i.e., by incorporating zonal or network capacity or supply constraints in a multi-activity framework by constrained nonlinear optimization. The result is an equilibrium solution for each simulation period, which means that these approaches ignore the lag structure associated with the adjustment processes they assume. Despite their rigour and elegance, the substantive scope of these unified approaches is limited. To date there is no comprehensive unified model of urban change encompassing besides the traditional location/interaction interface models of demographic change and migration, labour mobility, or the housing and land markets.

There are only very few models in the world today that attempt to incorporate all or most of the above aspects of urban change. These models typically operate with a combination of differently constructed submodels for different subsystems or change processes. Such models will be called composite models in this paper as opposed to the unified models discussed above. Composite models have the great 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 essential two-way information 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 of the modeller in which sequence the submodels are to be executed may be crucial. To decide that submodel A is to pre-cede 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 utilize 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 his decision on submodel sequence, the modeller in fact 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 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 5 or more years are grossly inadequate to capture the dynamics of urban change. For that, a period length of one year should be considered the maximum, if only Level 1 and Level 2 processes are to be modelled, and an even shorter period length is required, if also Level 3 changes are of interest.

Fully Dynamic Models

An interesting way to arrive at fully dynamic urban models is to interpret the convergence to equilibrium of static models as an adjustment process over time. This permits the investigation of the time path of an urban system as a sequence of equilibrium-seeking steps which may or may not arrive at equilibrium depending on exogenous influences.

One of the most-published modelling innovations of this kind is the demand-driven location model derived from the Harris-Wilson shopping model (Harris and Wilson, 1978). The basic idea of the model is ingeniously simple: it starts from the production-constrained shopping-trip model of the Lakshmanan-Hansen(1965) type and interprets its column sums, depending on their sign, as unsatisfied demand or excess supply and uses this information to drive the growth or decline of retail facilities (see, e.g., Beaumont et al., 1981):

$$\dot{W}_j = \varepsilon \left[\sum_i \frac{W_j^\alpha \exp(-\beta_1 c_{ij})}{\sum_j W_j^\alpha \exp(-\beta_1 c_{ij})} e_i P_i - k W_j \right] W_j \qquad (1)$$

where the W_j are retail facilities in retail zones j, the e_i are shopping expenditures of population P_i of zones i in j, k indicates the costs of supplying retail services in j, and ε is an elasticity parameter determining the speed of the adjustment process, and β_1 the parameter of te deterrence function. In the absence of external stimuli, the model produces logistic growth of shopping centres up to a spatial equilibrium, but due to its nonlinearities it displays a variety of bifurcations for different combinations of its parameters α, β_1, and ε, and for different initial distributions of P_i and W_j.

For the purpose of this paper, the question to be asked is how the model treats time. On the positive side it is noted that through the parameter ε the speed of the adjustment process modelled can be controlled and is not determined implicitly by the period length. Also explicit delays, although not present in this formulation, might easily be introduced. On the critical side, the first point to be made is that the model, like all spatial interaction models, predicts a slow process, establishing retail facilities, from a fast process, shopping trips, but it must be conceded that retail is the one case where this causal direction is not altogether unreasonable given the relatively free choice of customers in a surplus society. Much more important is the point that the model fails when the difference in equation (1) is negative, i.e., when the model in the case of excess supply predicts decline. If that occurs, it becomes apparent that the spatial interaction model confounds Level 1 changes (construction) with Level 2 changes (activity location) and Level 3 changes (mobility). In particular, the model is unable to distinguish between the different degrees of reversibility associated with the processes on each level, and consequently will in this case overpredict derelict stock at one place and growth at others.

The failure of the model to recognize the inertia of the existing stock becomes even more pronounced where it is used to predict the evolution of residential structure (Beaumont et al., 1981):

$$\dot{H}_i = \eta \left[a \sum_j \frac{H_i \ \exp(-\beta_2 c_{ij})}{\sum_i H_i \ \exp(-\beta_2 c_{ij})} E_j - H_i \right] H_i \qquad (2)$$

where H_i are dwellings in residential zones i, and E_j are workplaces in work zones j. H_i is the attractiveness of the housing supply in i and is defined as an additive function of supply volume, accessibility to retail, and housing density, the latter with a negative sign. The coefficient a indicates the number of households per worker, the parameter η is an elasticity corresponding to ε in equation (1), and β_2 is the parameter of the deterrence function It is obvious that the first expression in the brackets represents the sum of work trips ending in i. Numerical experiments conducted with this model (Beaumont et al., 1981) produced oscillations in the housing stock that have no resemblance with the evolution of real cities. It is simply not true that unattractive housing stock is immediately removed, rather it will go through several phases of filtering down and degradation or upgrading and reappearance on the market, depending on the specific economic situation and legal and political framework existing at that time, and only a minimal share of dwellings will eventually be demolished, mostly in the course of displacement processes, i.e., in order to make way for other more profitable land uses. Of course, nothing of this sort is reflected in the dynamics of this model. Obviously, the authors are well aware of this problem. In one experiment

(Clarke and Wilson, 1981) they ruled out decline altogether, but as decline exists, this is hardly a solution to the problem. The conclusion is that it is necessary to recognize physical growth (construction) and physical decline (demolition) as two separate, interrelated change processes with different time structures.

Another question to be asked about this model is how it takes up exogenous information. It appears that most of the drama displayed in the experiments published is due to the fact that extremely unlikely initial conditions such as uniform distributions of population, retail, and transport, were assumed. It would be interesting to know how the model would behave if it were fitted to data of an existing city and then started from that data. Most probably it would not move anywhere. The reason for this conjecture is simply that the model has no exogenous variables that could push it away from an equilibrium state once reached. For instance, if it is plausible that the "corner-shop to supermarket transition" (Wilson and Oulton, 1983) is mainly a consequence of growth in car ownership, this can be reflected in this model only by changes in its parameters ε and β_2 which may be more difficult to predict than the size of the shopping centres themselves.

Another well-known and much discussed dynamic urban model is that of the Brussels group (Allen et al., 1981). Their model approaches the issue of dynamics in urban systems from a different direction. It is based on the concept of self-organization through random perturbations found on the molecular or genetic level in physical or biological systems. The Brussels model is more elaborate than the one developed by Wilson and his colleagues as it has four industrial sectors and, instead of housing, two population groups. By some rearrangement, dropping of subscripts, and adjustment of notation, the corresponding parts of the two models can be made comparable:

$$\dot{W}_j = \varepsilon \left[\sum_i \frac{\left[A_j \, (k + c_{ij})^{-\beta_1}\right]^{\alpha}}{\sum_j \left[A_j \, (k + c_{ij})^{-\beta_1}\right]^{\alpha}} \, e_i \, P_i - (k + c_{ij}) \, W_j \right] W_j \qquad (3)$$

is the equation which in the Brussels model predicts growth and decline of retail facilities W_j in retail zones j, and

$$\dot{P}_{ih} = \eta_h \left[\sum_j \frac{R_i \, \exp(-\beta_{2h} \, d_{ij})}{\sum_i R_i \, \exp(-\beta_{2h} \, d_{ij})} \sum_s \xi_{hs} \, E_{js} - P_{ih} \right] P_{ih} \qquad (4)$$

is the equation in the Brussels model predicting population P_{ih} of socio-economic group h in residential zones i. Identical notations have the same meaning as in equations (1) and (2). It is immediately obvious that equations (3) and (4) are very similar to equations (1) and (2), respectively. The differences are of technical nature, e.g., in equation (4) ξ_{hs} is an inverse activity rate relating employment E_{js} of sector s in zones j to population of socio-economic group h instead of to housing, or lie in the definition and use of the attractiveness terms, A_j for retail and R_i for population. The different formulations of attractiveness are not discussed here, because in both models they do not seem to be based on any sort of social, psychological, or behavioural theory. Both, A_j and R_i, like H_i of equation (2), contain a measure of supply inversely related to density or crowding, so that the attractiveness terms, with the exception of W_j in equation (1), enhance growth, but prevent overcrowding. However the two models differ in the way they produce bifurcations. While in the Wilson et al. model bifurcations are systematically explored by parametric variations, in the Brussels model they are generated by random disturbances. The dynamic behaviour produced by the two models, however, seems to be very similar.

If the two models are so much alike, the critical comments made earlier apply also to the Brussels model. In particular, the inability of these models to distinguish between growth and decline and their different time characteristics casts serious doubts on their claim to be even prototypes of models of urban evolution. Given their wide publication and the high reputation of their authors, one can easily imagine a wave of urban models following the recipe: take a few logistic equations, add some nonlinearities and noise, and get lots of interesting dynamics. The question is what one can gain by studying the dynamics of such models, an understanding of the evolution of cities or just of models (Sayer, 1979)?

A MULTILEVEL MODEL OF URBAN CHANGE

It is not the intention of this paper to propose a particular urban model. However, after so much criticism of other models, a few positive remarks on how time might be treated in models of urban change may be due. Therefore, in the final section of this paper the outline of an urban model is sketched that solves some of the problems by being multilevel in its temporal dimension. The background of this exercise is work of the authors for simulating long-term change processes in the urban region of Dortmund, FRG. The model does not exist in full, but most of its components are operational (see Wegener, 1982; 1983b).

Scope of the Model

The model approach is based on the conviction that, as a minimum, all nine change processes contained in Table 1 need to be included in a model of urban change, and these are (i) industrial construction, (ii) residential construction, (iii) transport construction, (iv) economic change, (v) demographic change, (vi) technological change, (vii) labour mobility, (viii) residential mobility and (ix) daily mobility.

Other kinds of changes, e.g., related to public facilities, utilities, energy, environmental resources, etc., may also qualify for inclusion, but are not considered here to simplify the discussion. One of the nine change processes, transport construction, is treated as exogenous, because transport investments are normally public. The eight remaining change processes are partly exogenous, partly endogenous. Each change process can be disaggregated into subprocesses just like Table 2 disaggregates demographic change.

Figure 1 shows a hierarchical representation of the nine change processes with two levels of subprocesses. On the lowest level, subprocesses are called process modules. They are the basic building blocks of the model.

Choice and Non-Choice Processes

The lowest-level processes or process modules in Figure 1 can be classified with respect to causation. Most of them are the outcome of a more or less rational decision by one sort of actor, actors being individuals, households, firms, landlords, investors, and others. However, some processes are not decision-based, such as aging and death. This distinction is relevant for model construction, because decision-based processes can be modelled with theoretically well-founded choice models, while others cannot. Non-choice processes, on the other hand, can be well modelled with probabilistic transition or Markov models, because they depend only on an initial state, a transition probability, and time.

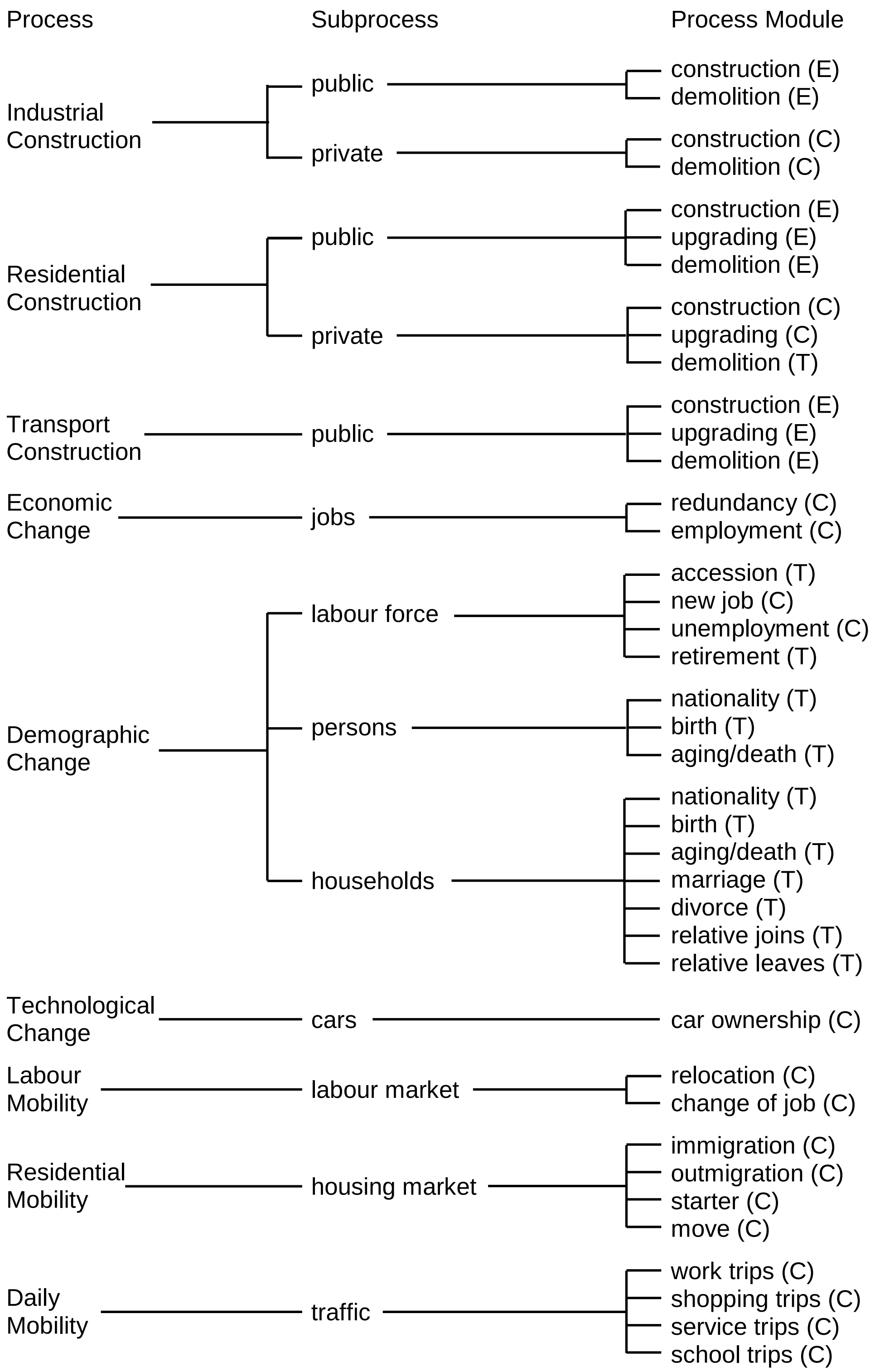

Figure 1. Process modules of urban change

The decision of the modeller whether a process is to be treated in the model as a choice or non-choice process is not a clear-cut one, but depends on the aggregation of the model and the perspective of the modeller. Only aging and death are positively not at the disposal of the persons involved, but, to name just a few, marrying, having children, being divorced, joining or leaving a household are. Despite of this it is common practice in demographic modelling to predict birth, marriage, and divorce probabilistically, i.e., as a non-choice process. This is reasonable, because the causal chains behind such processes are beyond the interest of the demographer. More generally speaking, if the causation of a process is of no interest for the purpose of the model, it can be modelled as a non-choice process, otherwise it should be modelled in a choice model.

Based on these considerations, the process modules in Figure 1 are classified either as choice modules, denoted by C, or as transition modules, denoted by T, with exogenous modules denoted by E.

Choice Modules

A choice module is a procedure simulating a probabilistic choice process in a given context. For this purpose, the procedure first generates a choice situation and then makes a choice based on random utility maximization. The simulation of a choice process in the choice module has four phases: a sampling phase, a search phase, a choice phase, and an aggregation phase:

- In the sampling phase, a decision maker or choice actor is sampled from all possible choice actors depending on the given context.
- In the search phase, the choice set is searched for a suitable choice alternative, and one alternative is selected.
- In the choice phase, a decision is made to accept the selected alternative or not.
- In the aggregation phase, the consequences of the choice are aggregated and executed in the system.

A typical choice module represents the behaviour of a household in the housing market (Wegener, 1983a). In the sampling phase, a household looking for a dwelling is sampled. It is assumed that its propensity to move depends on its satisfaction with its present dwelling. In the search phase, the sampled household looks for a suitable dwelling. It is assumed that it first chooses a zone in which to look for a dwelling, and this is not independent of its present residence and work zones. The household then looks for a vacant dwelling in that zone, guided by the attractiveness and price of vacant dwellings. In the choice phase, the household decides whether to accept an inspected dwelling or not. It is assumed that it accepts the dwelling if it can significantly improve its housing satisfaction. If it declines, it enters another search phase. In the aggregation phase, all changes of the relevant household and housing distributions, multiplied by the sampling factor, are performed.

Random utility choice models have first been introduced into transportation modelling (McFadden, 1974; Domencich and McFadden, 1975; Williams, 1977), and have been extended to modelling location (e.g., Anas, 1975; McFadden, 1978; Williams and Senior, 1978). The choice module concept is in effect the embedding of a random utility choice model in the framework of microsimulation. The principle of microsimulation consists in drawing sequences of random numbers and mapping them into cumulated probability distributions. This method has been first used in social science applications by Orcutt et al. (1961) and in urban simulation by Chapin and Weiss (1968), and has recently received new interest for its flexibility and ease of application (Kreibich, 1979; Clarke et al., 1980).

Transition Modules

A transition module is a procedure simulating a probabilistic transition in a given context. For this purpose, the procedure first generates an initial distribution and then performs a transition in it conditional on an exogenously specified transition probability. The simulation of a transition in the transition module has three phases:

- In the sampling phase, a transition object is sampled from all possible objects depending on the given context.
- In the transition phase, the transition is performed or not.
- In the aggregation phase, the consequences of the transition are aggregated and executed in the system.

A typical transition module represents the evolution of a household during a certain time interval (Wegener, 1983a). In the sampling phase, a household is sampled for processing, usually pro rata. In the transition phase, it is promoted to another household category with respect to nationality, age, income, or size conditional on the relevant transition probabilities for naturalization, aging, change of income, and birth of child, divorce, relative joins or leaves household, and death. In the aggregation phase, all changes of the relevant household distributions affected by the transition are performed.

Probabilistic models of transitions have been widely used in demography in the form of the cohort-survival technique and have been generalized to include migrations (Rogers, 1975) and more recently other transitions such as marriage, divorce, labour force accession, and retirement. An important extension of the multistate transition model has been the introduction of parametrized age-dependent schedules of such transitions instead of observed age-specific transition rates (Rogers, 1982). The use of parametrized schedules has many advantages, e.g., it permits substitution of missing data and projection of schedules into the future. Microanalytic transition models using Monte Carlo simulation have been applied, for instance, to modelling household formation processes (e.g., Kain et al., 1976).

Multilevel Linking of Process Modules

The process modules are linked by a file system and driven by a scheduler. The file system is a system of random-access datasets containing at each point in time a complete representation of the current state of the system and of all previous states generated up to that point by the model. The scheduler is a computer program to activate process modules in a specified sequence.

Each process module is designed such that it picks up all necessary information about the current and past states of the system from the file system and, after its operation, does all the housekeeping necessary to restore the system's consistency. Hence, no matter in which sequence the process modules are activated, each process module finds a consistent and up-to-date system and leaves one behind.

In an ideal model of urban change, the process modules would be initiated by the scheduler in a random order subject to probability distributions reflecting their frequency of occurrence in the real world. Such a model would, by totally dissolving the notion of a simulation period, optimally reproduce the interwoven fabric of events in time. Unfortunately, even with a modest degree of spatial resolution and contextual disaggregation, such a model would be too expensive to run on the present generation of computers (though probably not on the next one). Therefore, some degree of economizing through aggregation is required.

The idea how this can be achieved is simple, but requires some technical sophistication. It consists in establishing a temporal framework of nested simulation periods of different lengths as multiples of a very short incremental period, a month or a quarter say. If a process module is now activated by the scheduler, it is told the number of incremental units of time it is supposed to remain active. The process module takes this information to calculate the number of micro events to be processed during that time interval. If the number is large, the process module can increase its sampling factor or resolution and thus save computer time. Transition modules, beyond a certain level of aggregation, can be more efficiently executed in the aggregate, as Markov models.

The association of an appropriate simulation period to each type of process has to be determined along the criteria contained in Tables 1 and 2. This means that Level 1 or construction modules are called only once every few years, because their rates of change are so small and their impacts are so much delayed. However, large-scale investments or deinvestments like the construction or closure of a major plant or the opening of a major new transport line can be treated as historical events and entered into the simulation at exactly the time they occur. An advantage of this is that the number of times the transport model has to be run is kept as low as possible – a similar suggestion to that was already made by Batty (1976).

Level 2 changes, i.e., economic, demographic, and technological changes are called upon in a yearly rhythm. This corresponds to the one-year age groups normally used in demography and permits efficient aggregate models. However, Level 3 or mobility processes are processed on a monthly or quarterly basis to allow for the short response times in and between the labour and housing markets. Fortunately, this is not more time-consuming than a longer time period except for some initialization overhead, because these two process modules are microsimulations. Note that there is no transport model on Level 3. Instead, with each change of job or residence simulated in the labour or housing market modules, the trip tables affected are updated accordingly.

Of the process modules contained in Figure 1, only the labour market microsimulation presently does not exist. Operational microsimulation models exist for the housing market and for public industrial and residential construction. For the other process modules aggregate model versions are operational (Wegener, 1983a; 1983b). However, only a rudimentary fixed-period version of the scheduler program exists to date. It would be an interesting question to find out if the scheduler program might be equipped with a learning capacity, i.e., if it could monitor the rates of change generated by the process modules and modify their frequency of activation accordingly.

CONCLUSION

It has been the intention of this paper 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 urban theory at different times, it has been attempted to demonstrate that even the most recent efforts to capture time in dynamical urban models still have some way to go to become models of urban evolution.

In a short paper, hardly the surface of such an enormously difficult theme could be scratched. Nothing could be said about important topics such as data, calibration or validation, analytical solutions versus simulations, small or large models of urban change. However, it was felt that it was much more important to first sort out in our heads what the processes we are trying to model really are. But even that has not become clear at all. The more we try to understand, the more we have to confess that a lifetime after Patrick Geddes we have not made very much progress. Stumbling from the manifest to the mysterious, from the simple to the intricate, in the end we know only one thing certain: it changes.

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