The DELTA models and their applications

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Abstract

This paper outlines the development and applications of the DELTA package, which represents a major stream of applied modelling in the dynamic tradition pioneered by Wegener (reference Wegener paper in this volume). It describes the thinking that went into the prototype version in the mid-1990s, and how that has developed and continues to develop in a long series of projects undertaken since then. Having described the overall approach, the paper presents the sub-models that make up a working model. It describes the ways in which DELTA-based models have been used in practice, noting how the emphasis on economic impacts has grown over the period. The paper then addresses the issues of how the results from DELTA-based LUTI models can contribute to the formal appraisal (ex ante evaluation) of transport and land-use planning proposals. It concludes with some reflections on how the development and use of LUTI models may advance in future.

Key words

land-use modelling, land-use/transport interaction modelling, economic modelling, appraisal

Biographical note

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The DELTA models and their applications

Origins of the DELTA package

The development of DELTA grew out of work in the late 1980s and early 1990s on a series of transport strategy studies whose general characteristics were described by May and Roberts (1995). They involved transport models distinguished by wider range of demand and supply responses than was then usual, with much less spatial detail - the number of zones being typically one-tenth or less of that in "conventional" transport models of the same areas. The main models involved were gradually packaged as START (Roberts and Simmonds, 1997) and STM (Oldfield, 1993); other examples include APRIL (Williams and Bates, 1993).

One of the issues in those studies was the impact that the transport strategies being tested, some including major demand management interventions as well as transport investments, would have on urban development. In several studies this was addressed by the development "land-use change indicators". This approach (Roberts and Simmonds, 1997, section 4) involved a static model of activity location applied to calculate changes in land-use as the result of changes in accessibility in a future year. This was intended to provide a limited consideration of land-use effects that could be used within the conventional transport modelling practice of looking at alternatives in a single "horizon" year, rather than looking at the changes through time by which that future situation is reached. The method looked only at the changes from a previously-defined "base case" land-use forecast for the future years; it did not itself produce that forecast.

Whilst "land-use change indicators" proved moderately useful in practice, discussion around their use revealed a growing interest in questions which could only be answered by a complete land-use/transport interaction (LUTI) model, considering both land-use and transport markets within the familiar structure of interacting systems as illustrated in the centre of Figure 1. However, it was also felt that this needed to be easier to implement, more intuitive and more informative than the other LUTI models then available.

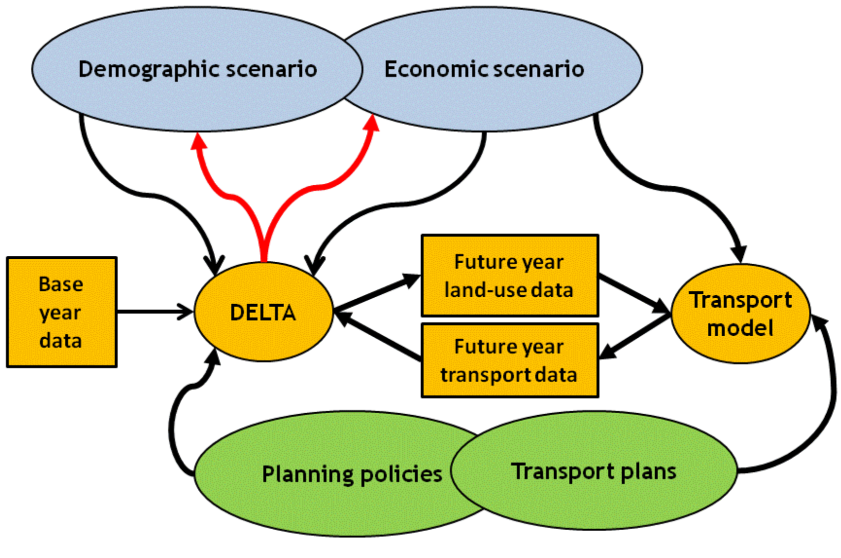

Figure 1 Land-use/transport interaction with scenario and policy inputs

The opportunity to develop such a model arose in 1995-96, in a project initiated by Professor Tony May at the University of Leeds Institute for Transport Studies, with support from MVA Consultancy. The author's firm, DSC, invested in the development of the DELTA design and software, and a prototype DELTA application was implemented (with help from ITS, particularly from Ben Still) and linked to MVA Consultancy's existing START model of Edinburgh (previously described by Bates et al, 1991). That model was a strategic transport model representing a single future year as conventionally described by "planning data" (households, population, retail floorspace etc by zone for that year). The prototype DELTA/START LUTI model involved running START at two-year intervals with the new land-use model updating the land-use data for each intervening two-year period. This prototype was used in research by Still (1997), and formed the centrepiece of a research project reported in Bristow et al (1997), Still and Simmonds (1997), Wardman et al (1997), and Simmonds and Still (1998).

The design and application of the DELTA Edinburgh provided the basis for the Greater Manchester Strategy Planning Model (GMSPM), commissioned by the Greater Manchester Passenger Transport Executive. Two important developments took place within that project: the addition of a car-ownership model, and the implementation of the accessibility calculations within DELTA rather than within the transport model.

A further major round of development followed from a commission to develop a "similar" model for the Trans-Pennine Corridor. The DELTA prototype was very deliberately a model of land-use within one urban area. The processes represented at the level of an individual urban area could not simply be applied on a large spatial scale (spanning 200km from Liverpool to Hull); instead, additional models of migration (for households) and of the regional economy (in money terms, but driving the distribution of employment) were added to the DELTA system. The Trans-Pennine Corridor Model (Simmonds and Skinner, 2003) was completed in 1999. The overall structure of DELTA has remained broadly constant since then, though all the components have undergone refinement and not all are used in very application. These refinements have not necessarily involved greater disaggregation of household or employment categories; in practice that number of household categories distinguished has tended to decrease. There has however been a big increase in the level of zonal detail represented. It was noted above that DELTA was originally conceived as working with spatially aggregate "strategic" models – and the first applications were very much of that kind. However, more recent work has typically linked DELTA to transport models with hundreds of zones (the most to date being around 1300). In other cases the DELTA modelling remains at a more aggregate level, either because the client organizations continue to use a strategic transport model in addition to a detailed one, or for reasons of land-use data availability (as in London, where the database for the present model was inherited from an earlier project). In some cases a detailed interface – in effect, a third spatial level of modelling – is used to convert DELTA outputs to finer transport model zones.

The overall design of the package

The initial design of DELTA was strongly influenced by the author's previous experience with earlier land-use modelling packages (particularly MEPLAN, TRANUS and the various ISGLUTI models[1]) and his experience with both strategic and disaggregate transport models. These influences led to three main requirements for the new package:

- observed data for the base year should be input, rather than having to be reproduced by the model;
- the model itself should work forward over time from that situation;

[1] Both Phase I (Webster et al, 1988) and Phase II (the series of papers from Webster and Paulley, 1990, to Paulley and Webster, 1991)

- the model should work in terms of processes of change recognizable in other research (in geography, urban/regional economics etc) and in informed conversation about housing markets, labour markets etc. In particular it should not make household numbers or locations wholly dependent on employment.

The choice of modelling **technique** was not obvious:

- microsimulation has many advantages, but would be difficult to reconcile with having housing and other prices or rents changing endogenously as a result of the balance between supply and demand (a valuable feature of the MEPLAN/TRANUS approach);
- we foresaw problems with Monte Carlo-type methods which require each forecast to be modelled several times, with "the results" being the average of multiple model runs[2];
- we saw the research value of microsimulation models which (like MASTER) allow the user to trace the history of the sampled individuals, but did not feel that this was a necessary characteristic for a planning tool;
- disaggregate modelling would be excellent for analysis of choice processes, but seemed difficult to combine with "non-choice" events (eg birth, death) or to repeated relocation processes in successive periods;
- obtaining disaggregate data would have been a further practical problem (since 1995 the production of synthetic microdata populations has become much more routine), and there was no call for disaggregate output (especially not given the aim of linking DELTA to existing transport models).

For these reasons we concluded that DELTA should be an aggregate modelling package. This made it practical to use iterative equilibrium-finding methods in some parts of the model, though given the dynamic framework these are incremental models and limited to very partial equilibria in particular aspects of the urban system.

Given the need to interact with conventional transport models, and to work with published Census data and similar, the treatment of space was taken as a conventional zoning system – initially at a highly strategic level (e.g. 47 zones for Greater Manchester), but later in greater detail.

The treatment of time was taken initially as two-year steps, as in the original IRPUD model; since the prototype, all models have worked in one-year steps. How often the transport model is run has proved a major practical issue. It has not been possible in any application to run the transport model every year – it is just too time-consuming. The best that has been achieved has been to run the transport model for alternate years (see Glasgow and Essex applications described by Aramu et al, 2006 and Dobson et al, 2007, respectively). Elsewhere the practice has generally been to run the transport model every fifth year, as shown in Figure 2. This is less than ideal, since land-uses can change substantially before any resulting congestion is calculated, but with some transport models taking >12 hours per modelled year it is unavoidable. This is of course not because individual transport models have got slower, but because DELTA has applied to larger areas and in many cases linked to "conventional" rather than "strategic" transport models with many more zones and much more network detail.

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[2] We developed a version of DELTA using Monte Carlo microsimulation for household/person modelling (Feldman et al, 2010). It was an extremely interesting exercise which offered a number of ways forward for further research, but the stochastic variation of results remained a major issue in potential use of the model (Simmonds et al, 2011).

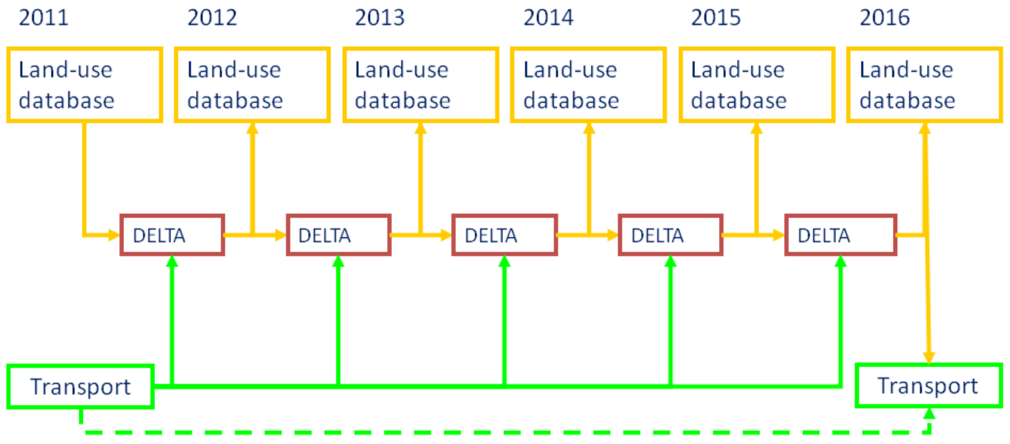

Figure 2 Time-marching sequence in DELTA, with five-yearly transport modelling

Package components

The package components can be considered in terms of those working on the economy and employment; those working on households and population; and those working on changes in the supply of spaces. The sequence in which they are considered in modelling changes for each year is such that

- earlier components are preparatory calculations (eg accessibility measures) or consider a part of the system (eg investment) using time-lagged inputs from other parts of the system without no immediate feedback; then
- later components deal with interactions between components, particularly
  - between households and housing (household location, housing market)
  - between firms and non-residential space (employment location, commercial floorspace markets)
  - and between firms and households (labour market).

This sequence means that

- demographic changes (birth, marriage, death) produce immediate changes in the demand for housing, both quantitatively (size of dwelling) and qualitatively (locational preference);
- locational change produces immediate change in the potential supply of labour from each zone;
- changes in demand for labour produce immediate changes in the employment status of residents;
- changes in employment status lead to changes in the demand for housing (or more precisely in the ability to afford housing and other goods/services), but these do not take effect until the following model period.

The direct interaction between firms (as employers of labour) and households (as suppliers of labour) thus takes place at the end of the process, once the numbers of jobs and households and their locations have been determined. This approach is thus the antithesis of the Lowry-model approach, in which both the numbers and the distributions of households are determined by the numbers and locations of jobs (see discussion in Simmonds et al, 2013).

Modelling the economy and employment[3]

The treatment of the economy and employment involves

- models of investment and production/trade at the area level, these components constituting the DELTA regional economic model (REM);
- a model of nominal employment location at the zonal level (within each area), representing the processes by which firms occupy space on the basis of the numbers they expect to employ;
- the joint use of the REM and employment location outputs to forecast actual employment (labour demand) at the zonal level.

At the upper (area) level,

- the investment model represents firms' decisions about the areas in which to invest - decisions which affect only a minority of total industrial capacity in each year and therefore respond slowly to change and have a lasting effect - whilst
- the production model forecasts the outturn taking account of the shorter-term changes in the economic scenario, the short-term influences of transport, and so on.

Similarly at the zonal level,

- the location model represents firms' decisions about where within each area to locate, given the investment decisions and the resulting space requirements, the competition for space and their requirements in terms of accessibility, whilst
- the final employment outputs forecast the outturn demand for labour given the results of the production model (and hence taking account of the shorter-term changes in the economic scenario, etc).

Each level of the model thus has one component which represents firms' choices about where they should locate their productive capacity; and one which represents outcomes from the interactions between firms and their markets.

The **investment model** works on the basis that firms need continually to invest or reinvest in productive capacity, whether this investment is in heavy industrial installations such as an oil refinery or simply in the equipment of an office. A proportion of capacity is lost each year (depreciation); the distribution of new capacity resulting from investment is by default the same as the existing distribution, but is attracted to areas where access to markets has improved and where costs have decreased. The investment model is an important influence on the working of the production/trade model for sectors which are widely traded across the modelled area. In addition, in some versions of the model, a simplified investment model is used directly as the economic model, without the use of the production/trade mode.

The **production/trade sub-model** is a conventional spatial input-output model in which the main categories of final demand are exports, government consumption and consumer demand. Exports and government consumption are exogenously specified as part of the overall economic scenario. Consumer demand is determined as a function of the total expenditure on other goods and services in the household location model (ie other than housing or transport). The pattern of trade is influenced by

[3] For key equations see Simmonds and Feldman (2013)

- the demand in each area (final demand plus intermediate demand calculated by the input-output process);
- the capacity of each area (resulting from the workings of the investment model);
- the cost of production in each area (costs of inputs plus value added);
- the costs of transport.

The production/trade sub-model has strong similarities to those in regional applications of the MEPLAN and TRANUS packages (Hunt and Simmonds, 1993). However, an important difference is that it is strongly influenced by capacity, i.e. the accumulated investment in each sector in each area, which gradually changes over time as a result of the investment process.

A recent refinement to the economic modelling is to integrate agglomeration effects and the productivity effects of changing employment location (previously considered only as post-forecast appraisal issues – see below) into the model itself. These effects (very similar to those recommended by the UK Department for Transport in their WebTAG guidance) modify GVA/worker (at a detailed level of employment activity, socio-economic level and zone). These changes in GVA/worker are assumed to result in proportional changes to wages. These changes in wages (less tax) lead to changes in household incomes, dependent of course upon the pattern of travel to work. Those changes in incomes affect the demand for housing, the demand for car ownership, and household consumer expenditure. This last change produces multiplier effects through the ordinary working of the spatial input-output model, whilst all of these changes have further consequences[4].

The **employment location process** is driven by the changes in demand for space to accommodate workers. The changes in workers by area and sector are derived from the outputs of the preceding economic models, except in zonal-only models where they are directly input as part of the exogenous scenario. The employment location model then locates these jobs to zones; this involves competition for available floorspace, so this is also the "commercial property markets" model. The location process itself is an incremental one which assumes that jobs in each employment activity and area will tend to remain distributed as they were at the beginning of the modelled year unless they are influenced by changes in

- floorspace supply,
- accessibilities, or
- costs of location (through changes in rents).

Changes in floorspace supply come either from the model's own forecasts of development (themselves subject to planning policy constraints) or from exogenous inputs representing particular developments (and/or demolitions). Changes in accessibilities are calculated within the model each year; each employment activity can in principle be sensitive to a slightly different measure of accessibility depending on the weight attached to accessibility to labour supply (by socio-economic group), to residential customers, to business clients and so on. The changes in costs of location are calculated as a function of floorspace rent and floorspace per employee; other costs of location can be input either as a fixed cost per m^2 or as a multiple of rent (which is more appropriate for business rates). Floorspace per employee is elastic with respect to rent. Rents are iteratively adjusted until a combination of density

[4] A paper describing this version of the model and its background is in preparation (Bosredon et al, forthcoming). It has been quite extensively used e.g. as the basis for the West Midlands Dynamic Economic Impact Model (West Midlands Combined Authority, 2016)..

and location changes equilibrates the current demand and supply of floorspace. Only a proportion of existing employment is open to relocation in each year, reflecting the limiting effects of relocation costs, of leasehold terms and so on.

Note that throughout this sub-model, activities only interact if they are competing for space. The sub-model is in effect a separate property market/location model for each floorspace category.

The final stage in modelling employment in each year is to convert jobs by zone, and employment sector into numbers of workers by zone and socio-economic level. This provides the basis for the model of how the labour supply will fill these jobs, considered below. Note that in all DELTA models to date it is assumed that all defined jobs are filled, ie there is no provision for jobs to be left vacant. This is a simplification in modelling labour markets which may need to be modified in future, but until now it has been considered essential for the coherence of the forecasts – allowing unfilled vacancies might for example understate the congestion resulting from a given scenario.

Modelling household and population

The modelling of households and population involves modelling

- demographic change, given households' location at the start of the year being modelled;
- changes in car ownership proportions;
- household migration (longer-distance moves between areas) and location (within areas), the latter involving modelling the housing market;
- employment status and commuting, and the conversion of household location forecasts into population location forecasts.

The non-household population can also be accounted for, and is usually included, if only to model a population scenario that directly matches external projections (few if any transport model consider the non-household population as either producing or attracting travel).

The **demographic change** component deals with change m in terms of household formation, dissolution and transformation; households are converted into population later (by the employment/commuting component). We do not claim that this kind of household modelling is a sufficient, independent demographic forecasting model (though there is interest in this technique within demography - see for example the papers in Keilman et al, 1988). On the contrary, it is intended as a way of producing the detail required for land-use/transport modelling given an overall scenario produced by more conventional demographic models.

The transition model typically works separately for households of each socio-economic group. It could also be used to apply exogenously-determined rates of movement between socio-economic groups. Change within the study area in household numbers is expressed as rates of:

- household formation (e.g. the probability of a child leaving home and setting up as a single-person household);
- household transition (e.g. the probability that a couple-without-children becomes a couple-with-children);
- household dissolution (the proportion of households of each type that cease to exist in each period).

More complex changes are treated as combinations of the above processes. The set of household types chosen for DELTA has to be sufficient to capture the main stages of the human life cycle and the main characteristics of household formation. The modelling of household changes influences the mobility of households and hence their scope for response to transport or other changes: newly formed households have to be located, and households that have changed "life stage" are more likely to relocate. Household dissolution and departure and the proportion of surviving households who may move define the supply of "second-hand" housing. A large proportion of households are "immobile" in each period and their housing does not come on the market.

The usual **car ownership model** is based upon the national car ownership model developed by Whelan (2001), converted into a zonal and incremental form. This forecasts changes in households' car-ownership as a function of income, employment, licence holding, car running cost, car ownership cost and company car distribution. Car-ownership is treated as conditional on location.

Migration into and out of the overall modelled area is usually defined as a proportion of each household type that will leave in each period, plus a ratio of arrivals to departures. This formulation allows for different levels of migration both by household type and by socio-economic group. We recognize that migration is often of individuals rather than whole households, and that modelling migration in terms of households is an approximation.

The processes of household migration **within** the area modelled are based upon the concept of different "types" of moves, over different ranges of distance, driven by different influences. This approach has been influenced in particular by the multi-stream models developed by Gordon and Molho (1998), who identified:

- national (inter-regional) moves driven primarily by economic factors;
- intra-regional moves driven particularly by environmental and "lifestyle" factors;
- local moves driven mainly by housing.

The first two are referred to in DELTA terminology as "migration", and are usually modelled as a single stream. Local moves are represented in the location sub-model (below).

The migration modelling is based upon "push" and "pull" factors which are largely calculated from other variables within the model, together with exogenously defined "environmental" variables and a set of distance deterrence function. Different influences, deterrence functions and propensities to migrate can be specified for different types of households.

The **household location sub-model** is both the "household location/relocation model" and the "housing market sub-model". As previously noted, it works on the subset of households and housing that are in the market in any one year. The process takes account of:

- changes in housing supply (from the development model);
- changes in accessibility (from the transport model and the changes to other land-uses);
- transport-related changes in the local environment (from the transport model);
- housing quality (from the quality sub-model);
- the costs of housing (based on rents adjusted within the sub-model) and the amount of floorspace and other expenditure that households can enjoy given those rents

in each zone[5].

Relocating households are also affected by the distance from their initial location to each other zone; these relocations are not limited by area boundaries (ie households can make relatively short-distance moves from one area to another).

The model assumes that potentially relocating households will on balance remain in the same location unless there are changes in one of the variables listed above, and that newly locating households will locate in proportion to the previous location of households of the same type unless, likewise, there are changes in one or more of the variables.

The changes in accessibility, environment and quality are changes over a period of time (one or more modelled periods) ending at the beginning of the present period. The lengths of these periods is inversely related to the frequency of moves for households of each type.

The modelling of the relationship between households and housing was initially very similar to that of the Martin Centre models (see Hunt and Simmonds, 1993), even though the location models are different, and even though within DELTA the process operates only for a subset of households in each period. Households are treated as renting a variable quantity of floorspace. As in the Martin Centre models, a function is used which maximizes the utility that the household can obtain, given its budget and preferences, at the current level of rent. The rent of housing in each zone therefore influences both how many households of each type will choose to locate in each zone, and how much space they will each occupy. The operation of the model involves iteratively adjusting the rent in each zone until the total space "consumed" (ie space per located household times number of households, summed over all household types) equals the space available less the amount less vacant. The vacancy rate varies with the rent.

The use of floorspace per household as a continuous variable, rather than modelling the relationship between households and discrete "dwellings", can be seen as allowing the model to avoid a great deal of the detail that would otherwise be needed in order to consider the ways in which households match themselves to dwellings or convert dwellings to their needs.

An additional and important element of change over time is introduced by increases (or possibly decreases) in household incomes. Future household incomes are input for each household type, so that the model would respond differently to different distributions of income across socio-economic or age groups. Households of any one type change income as a result of gaining/losing employment (and, in the latest versions, as a result of agglomeration effects acting on wages).

This **employment/commuting component** completes the household/population changes by adjusting the employment status of households, and the associated home-work matrices, so as to fill the jobs at each socio-economic level in each workzone. It thus models household members' choices of whether and where to work, subject to matching the demand for labour. Different versions of the model work either by adjusting wages or by an iterative adjustment of the home-work matrices and the proportions of adults in work. The proportions of adults in work are subject to constraints representing a scenario for labour market participation. The adjustment of employment status is carried out each year; this is consistent with estimates that levels of employment within strongly connected labour market areas do adjust within about a year. The model can allow workers of different socio-economic level from that of their household; even with only four socio-economic levels, many households contain workers of different levels.

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[5] For key equations see Simmonds (2010).

The one other function of this sub-model is to add to households their economically inactive members, ie children, retired persons, and other economically inactive adults.

Supply of floorspace – quantity and quality

The development model works in three steps, applied separately to each modelled floorspace type. It first calculates the total quantity of development which developers will seek to build, as a ratio of new to existing building, usually with an elasticity with respect to expected profitability (see Bramley, 1993). Profitability is estimated from the most recent rents and input construction costs.

Secondly, this total is if necessary constrained to the floorspace which the planning policy inputs will permit during the year being modelled. Note that in an unconstrained situation, making *more* land available will have no impact on *total* development, though typically it will modify its spatial distribution.

Thirdly, the constrained total is allocated to available land in zones using a model with a strong positive relationship to profitability. Recent versions of the model also include a viability term, which ensures not only that development is more likely in more profitably zones, but that it does not occur at all in zones where development is manifestly unprofitable (for evidence on the extent of this problem in British cities, see Jones et al, 2009). Permissions also act as an absolute constraint; any excess development is reallocated to other zones.

There are several features which further elaborate this sub-model, chiefly:

- development can be specified by the user as definitely occurring rather than just being permitted; such development is added to the stock in the specified year regardless of market conditions or the level of permissible development available. This facility is typically used both to represent development observed since the base year and to specify what-if tests. Whilst “exogenous development” is user-defined, its introduction can influence the “endogenous development” forecast in subsequent years. Demolition can also be specified;
- whilst the amounts of new development permissible are defined by the user, the scope for redevelopment, either to build more of the same type of floorspace on currently developed sites or to replace existing floorspace with different types, can be calculated within the model. This is done as a calculation of additional “permissible development” controlled by coefficients including policy indicators which specify which kinds of floorspace can be redeveloped to which other kinds, and the degree to which densities can be increased. This additional permissible development is then considered along with the new development possibilities in the second and third steps of the basic development model as defined above.

The other process of change in the supply of floorspace considers how the **quality** of different areas of the city varies over time. This is a subject much discussed in planning, but one which has rarely been addressed in modelling. To date it has mainly been applied to housing.

The hypothesis behind this sub-model is that the inhabitants of a zone influence its characteristics in ways which gradually affect its desirability as a place to live. Technically these effects are externalities. Actions with positive external effects include improving gardens, planting trees, etc. Actions (or inaction) with negative effects include neglect of buildings and gardens, or use of residential property for "industrial" purposes (eg breaking up cars). Vacant property can have a marked negative effect.

This is implemented on the basis that:

- "quality" is be measured in terms of a premium (or discount) on rents, due to the higher (or lower) than average levels of the relevant characteristics
- quality moves asymptotically towards a level that reflects average income and vacancy;
- quality changes only fairly slowly, so for example a sudden increase in vacancy will only gradually affect quality.

Quality changes can also be introduced exogenously to represent the effects of interventions to improve the housing stock and its immediate environment. This sub-model is important to the overall design of the model, because it represents a process of "positive feedback" that should be able to represent the widely observed virtuous or vicious circles that tend to maintain or to increase the differences between prosperous and deprived areas within cities. In this it contrasts with the environmental feedbacks which work through the transport model which often give rise to negative feedbacks.

Use of the package – key model forms

Not all of the sub-models are used in every application, and there is a growing range of variation in details where they are used. The applications can be broadly grouped into three:

- models of individual towns or cities using only the lower-level (zonal) components of the model;
- sub-regional models, using the zonal components plus the migration model and a simplified economic model;
- regional, multi-regional and national models, using the full system, ie including the spatial input-output model.

In addition, not all components are used every time a given model is run – for example, a sub-regional model may have the characteristic that total employment in the sub-region varies in response to the consequences of policies being tested, but the model may on occasion be run with fixed total employment as a what-if test. “Switching off” is increasingly used to help analyse the contributions of different processes to overall results.

Applications and results

DELTA models have been developed for a wide range of purposes, ranging from assessment of a specific infrastructure proposal, through those built to test the range of proposals within a particular study, to those created to provide the agency commissioning them with the means to examine a wide range of potential scenarios and interventions not necessarily identified at the outset of the project. Some have been used extensively by the client agency’s own staff or by other consultants working for them. There is accordingly a very wide range of tests that has been carried out, each of which has produced a large volume of results. This section tries to reflect that range of material within the limits of the space available. Many of the individual models have of course been used in different ways, for quite different purposes, over their lives - an example being the South and West Yorkshire Strategic Model (Simmonds and Skinner, 2003) which was originally developed and used to test a small number of scenarios and packages within a particular study, but was subsequently used in follow-up work for planning agencies within the modelled area, and then as the basis for an extensive package of research for a government review of transport planning and investment (see Feldman et al, 2008).

A first category of model use is that where the model is used primarily to create future land-use inputs for a transport model. In one or two cases, this has been done using the land-model with very simple transport cost inputs calculated from distances, without using a transport model proper. In the majority of cases, it is done as a run of the full land-use/transport interaction model, with the transport outputs from one transport model year influencing the patterns of land-use change in the following years. In such modelling, the focus is largely or entirely on the results that are passed to the transport model, ie the distributions of persons, jobs and other transport-demand-generating variables. A regular topic of discussion with land-use planning agencies is the relationship between the model outputs and other population or employment projections - see discussion about scenario-matching under "Appraisal". An equally regular topic of discussion with some of our transport modelling colleagues is the complexity of the relationship between the land-use planning inputs to the model (particularly those for housing) and the population outputs of the model. The scope for changes in the mix of households in each zone, and for changes in the numbers of household accommodated within a given stock [explain case for variable floorspace/household], mean that the correlation between physical development and population change can be weaker than expected, expect where very substantial volumes of building are concerned. The models regularly serve to provoke discussion of the questions of how a growing and changing population will be accommodated within an insufficiently changing stock of dwellings, and to suggest answers - which in England, at least, usually indicate a worsening shortage of housing.

Secondly, models have been used to test how the future distributions of population and households are likely to vary with different assumptions about transport costs and behaviour. Such tests have looked for example at the impact of

- major increases in the costs of car use
- major increases in the costs of all motorised transport
- increases in home-working such that the number of trips to work per worker decreases significantly
- major increases in the attraction of city-centre and inner-city living.

On some occasions, the interest in the results is in the land-use impacts themselves; on others, it is on those land-use impacts as generators of transport demands. All of these illustrate a common feature, which is that something may be tested as a "scenario" which might in fact represent the outcome of a set of undefined policy measures - for example, an increased attraction to city-centre and inner-city living might be the result of an exogenous change over time in household preferences, but it might also result from a package of policies deliberately created to achieve such an increase. In many cases, such "scenario" tests represent an initial "what if?" examination of something which could be examined in much more detail using the same model system with more specific policy inputs.

The third group of model uses are those that involve testing transport interventions. The traditional focus is on modelling (and subsequently appraising) the impacts of investment, but model applications have also looked at the impacts of management measures (eg reallocating existing road capacity to bus lanes or cycle lanes) and pricing (including road user charging). Examples include

- Edinburgh and Manchester road pricing proposals;
- management measures as part of the Trans-Pennine and South/West Yorkshire packages, and of Local Sustainable Transport Fund interventions;

- road investments including M74 Completion, A8 upgrading, A9 and A96 upgrades, all in Scotland; M1 improvements in Yorkshire, numerous road schemes in South Yorkshire, South Essex and Leicestershire;
- rail investments including various Transport for London schemes; tram or tram/train schemes in South Yorkshire; Edinburgh and Manchester trams; Glasgow tram/subway schemes; Edinburgh-Glasgow high-speed rail; Airdrie-Bathgate rail reopening.

Fourthly, testing land-use planning interventions. Some of the DELTA applications are used extensively to examine the consequences of major development proposals and of development plans. The Leicestershire and South Hampshire models, for example, have been used regularly for this, as has the national model of Scotland (TELMoS). In most cases, given the absence of a formal approach to appraising the land-use consequences themselves, the main interest is in the eventual transport impacts of the land-use development. In the case of development plans for local authority areas, the same lack of a formal approach to appraisal against a recognizable "base case" means that there is often a difficulty in defining how "the impact of the plan" should be measured. One feature of this kind of work especially for the assessment of specific developments is that there is often interest both in the "most likely" impacts of the development on traffic flows and the "worst case" impacts; the proposer of the development would prefer to consider the former, whilst the local authority may consider that it needs to consider the latter (all with the nuance that in some cases it is the proposer who is paying for the analysis but the local authority controlling how it is done). The issues arising from this have led to the development within DELTA of additional features allowing new developments to be input in different ways in order to specify different kinds of "what-if?" questions relative to a given reference case. These include

- "what if this development is allowed?" - specifying the additional development as a possible addition to the stock of floorspace, and allowing the model to forecast when (or if) it will be taken up
- "what if this development happens?" - specifying the additional development as a definite addition to the stock;
- "what if this development happens and attracts these households?" (or these jobs, for an employment development). This allows the modeller to test the consequences of the development taking account of the developer's or the local authority's view on the likely occupiers, and also to assume that these households and/or jobs are either
    - wholly additional to the reference case scenario for the area in question, or
    - partly additional, or
    - not at all additional (occupied in the first instance entirely by households/firms who would have been present anyhow).

Note that even in the "wholly additional" variant of this last case, the model is still doing more than simply adding the specified households and/or jobs to the reference case forecast, in that

- additional residents will compete for employment with other residents;
- additional jobs will compete for workers with other jobs;
- additional jobs and the resulting incomes will generate multiplier effects;

- if the occupiers of the development are not "wholly additional", then the addition of the development into the property market may have time-lagged effects of either drawing in additional households/jobs from elsewhere and/or reducing development in subsequent years.

In this kind of analysis the focus is very much (and very intensively) on the results in terms of the forecasts land-uses for the zone(s) where the development is planned, and perhaps for neighbouring zones. The debate about the assumptions to apply can itself be constructive, especially in cases where both developers and local planning authorities may be tempted to present the prospective occupiers of potential development as net gains to the local population and economy, in ways which are not always justified by the available evidence.

Fifthly, other kinds of interventions. Transport interventions generally enter the model through the transport model, as changes in generalised costs of travel or transport. Land-use interventions mainly enter as changes in the controls on the supply of floorspace, or as taxes or subsidies on development or as taxes on the occupation of floorspace. A wide range of other interventions can be tested if it is possible to prepare an exogenous estimate of

- their impact on investment
- their impact on exports
- their impacts on firms' or households' willingness to pay to locate in a particular zone or zones
- impacts on individuals' willingness to travel to/from particular zones (ie non-transport changes in generalised cost).

In the last case, the interventions are introduced into the model as suitably scaled changes in the quality or environment variables. This facility was used extensively in work on schemes proposed for inclusion in the Sheffield City Region Investment Fund (see Revill et al, 2014), and in similar work for Glasgow and the Clyde Valley. The schemes tested by varying direct inputs to DELTA (i.e. excluding transport schemes) included

- site remediation (leading to lower development costs for the private sector);
- improvement in access to key sites;
- improvements in quality of urban public realm, and green infrastructure;
- district heating schemes;
- specialised investments in industries supporting the renewable energy sector;
- tourist developments targeted at attracting additional tourists from outside the region/nation;
- flood prevention; and
- provision of access to high speed broadband.

Clearly, with many of these, there is much that has to be done outside the LUTI framework that is critical to the assessment of the investment in question; but there is a considerable advantage to having a single model which can be used to estimate the impacts once they have been converted into a usable form.

That point leads to the final category of applications, in testing the impacts of packages of interventions. One of the advantages of a more extensive model (compared for example to using separate land-use and transport models) is the facility to test packages of interventions in a manner which takes account of the interactions between them. Again, the work for the Sheffield City Region provides a recent example, and some of the findings regarding packages of schemes are discussed in Revill et al (2014).

Appraisal issues

By appraisal we mean the assessment of the benefits and disbenefits of a scheme or package whose impacts have been forecast using the model, including formal cost-benefit analysis.

In so far as there can be said to be a "traditional" use of land-use modelling results, it has been in a "traditional" context where economic and demographic growth is taken as given (not modified by policies being appraised), and the LUTI modelling is used to forecast spatial impacts of planning/transport interventions. Forecasts of the impacts of interventions are then used as quantitative inputs to a qualitative assessment of whether the impacts were supportive of

- regeneration objectives
- other policies

Examples of this have included analyses of:

- policy packages emerging from South and West Yorkshire Multi-Modal Study
- proposals for completion of the M74 (around Glasgow) and for the Airdrie-Bathgate railway reopening.

From the early 2000s onwards, there has been a growing interest in net economic impacts, which have been considered as part of the appraisal process rather than as part of the modelling process (see Feldman et al, 2008). Current developments may bring these within the scope of the model itself, instead of the appraisal.

More recently, there has been a sharp increase in interest in local economic impacts, with local agencies in the UK being encouraged to assess interventions in terms of whether they will help to grow the economies of the agencies' areas, whether this represents net growth to the national economy or is at the expenses of other areas within the country. DELTA models used intensively to calculate economic impacts of proposed land-use/transport/other investments in Sheffield and Glasgow City Regions, and the theme is also being taken up elsewhere. This element of appraisal is linked to arguments about the degree of centralisation in UK government, in particular the argument that centralised appraisal criteria based on national-level welfare objectives tend to stifle local economic growth by forcing local agencies to concentrate on interventions that meet those criteria rather than on the interventions they would choose to benefit their own areas (see Volterra, 2014]. In a number of DELTA applications, local benefits are estimated on the basis of

- more jobs, forecast by the model itself;
- improved productivity, calculated by a post-modelling agglomeration calculations;
- savings for business travel/freight movement, calculated from the transport model outputs,

in each case considering only gains or savings accruing within the boundary of the agency's area (which itself is always smaller than the modelled area) (see Minta et al, forthcoming).

A further potential approach is to extend cost-benefit analysis to cover the full land-use/transport/economic system represented in the models. Standard DfT (WebTAG) "transport economic efficiency" (TEE) analysis (ie consumer surplus changes based on trips and generalised costs) can be misleading if land-use changes are involved, and official advice is that it should only be used where the land-use/economic data is the same in the Base and Alternative. We have developed the basis of an approach to apply cost-benefit analysis to the land-use/transport system rather than just to the transport system - known as LUTEE – (land-use/transport economic efficiency); the design to date was described in Simmonds (2012). Work so far has focussed on measuring benefits to households (instead of to non-work travellers). The core of the approach is to measure changes in consumer surplus for households by zone rather than for travellers by origin/destination/mode etc.

One issue that has become increasingly important as a result of the use of LUTI models in appraisal is the definition and content of the "base case" against which "alternatives" are appraised, particularly for larger regional or national models where other spatially-detailed projections are also in use as the basis for other aspects of the planning processes. By default, a LUTI model whether based on DELTA or any other package will produce its own forecasts of "base case" growth by (say) sub-region or local authority. If these differ significantly from the other projections, it can cause problems in the use of the model results, especially where for example the "base case" land-use policies are intended to conform to those other projections. It can of course be argued that no one model is certain to be correct, and that plans should be made on the basis of multiple projections or scenarios rather than on a "single-shot" basis; however, where the local planning process is required by central government regulation to set plans for housing development on the basis of particular projections, such an argument is not constructive from the local government point of view. There is also the issue of what information, and which effects, are taken into account in which kind of model. Detailed economic projections models may well use much more detailed information about the performance of different sectors in different parts of the country than can be incorporated in the DELTA economic modelling (though some of that information may be in the form of recent trends rather than more explanatory variables).

The approach that we have adopted to deal with this constructively is to develop methods of controlling an initial model run – called the "scenario-matching case" to match the other projections at appropriate levels of detail (e.g. sub-regional employment forecasts by sector) whilst taking care that the other assumptions made in the "scenario-matching case" are consistent with the assumptions made in the preparation of those other projections. This typically involves producing a controlled run of the model with no changes in transport costs (or only those directly related to the economic scenario, such as changes in fuel costs and values of time), and with changes in floorspace supply which result in no changes in rents – in cases where the other projections have (often implicitly) assumed no such changes. Note that this process is not regarded as one of calibration, and whilst it may involve constraint mechanisms they must be such that the model can then pivot around the scenario-matching case when run with other inputs (for an example of such methods for use of local projections, see Dobson et al, 2009). The Base Case proper is then produced by running a test with the transport model in use (so that changes in congestion lead to changes in transport costs) and with actual rather than hypothetical planning policies which may well result in changes in rent. This Base Case will differ from the external projections, but the differences will be due (directly or indirectly) to the transport and planning assumptions that differ from those used implicitly or explicitly in the external projection process. This provides an appropriate and constructive basis for further work, although of course scope for debate remains both about which external projections should be used and about what implicit assumptions may be embedded within them.

The application of the FLUTE model for the Sheffield City Region (Revill et al, 2014) represents current "best practice" in this respect: the scenario-matching test was run so as to match an exogenous scenario defined by the Department of Transport (the National Trip End Model (NTEM) projections) with hypothetical transport and planning policies giving no change in congestion and no change in non-residential rents, and the base case for policy testing was then run with do-minimum transport investment and current planning policies, with the scenario for the region being allowed to vary from the exogenous scenario in both employment and population.

Reflections on possible future developments and applications

One line of development that seems particularly clear is that land-use/transport modelling will continue to be more closely linked or integrated with spatial economic modelling. The papers in the present volume reflect progress in this direction, though it probably still understates policy-makers' interest in such integration.

How this linkage or integration will progress remains to be seen. One path would be for more processes and responses, and more detail, to be incorporated directly into the models. Another that is applicable in some respects is using LUTI models to pivot about economic models that do not consider either land-use or transport explicitly, but which take greater account of other variables – as in the scenario-matching process described above.

The questions of further enriching the economic aspects of these models is obviously related to the issues of model complexity. Lee's famous (or notorious) *Requiem for Large Scale Models* (Lee, 1973) argued that above some level of model complexity, what is learnt from a modelling exercise about the "real world" diminishes, and what is learnt is only about the model system; for model application in the "real world" there is therefore an optimum point, involving a relatively simple model, which maximises the value of the results obtained. Such a risk remains, but it would appear the Lee underestimated the benefits (a) of models drawing on research in other academic disciplines, (b) of using modelling packages where understanding of the model is developed across multiple projects, and (b) of an approach which allows at least some of the component processes to be switched off whether to produce simplified tests for particular what-if purposes or simply to understand relative contributions. (In fairness to Lee, few if any of these characteristics would have been observable in the modelling experience he could review when he wrote the paper.)

Note in particular the role of positive feedbacks – whereas many past LUTI applications (including earlier DELTA ones) have worked with assumptions and constraints that meant that most feedbacks were negative, increasing interest in economic effects including agglomeration (with the possibility of net change in study area totals) and attention to how planning policy may respond to changing conditions, means that positive feedbacks are increasingly possible. Whilst these are often interesting and sometimes very welcome to the end users of the model results, they can also be more surprising and sometimes more difficult to explain.

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