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Review of land-use/transport interaction models

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SUMMARY

This report reviews the range of current land-use/transport interaction (LUTI) models in terms of their potential contribution to transport appraisal. It considers those models used in current or recent planning practice and in academic research which represent real (rather than hypothetical) cities or regions, and which can forecast at a minimum the impacts of real (rather than abstract or stylised) changes in the transport systems of those cities and regions. The focus is on design and scope, not software availability or price.

The models are classified primarily in terms of their treatment of

(a) time - from static models with no time dimension at all, to models in which all processes and relationships involve explicit time lags - and

(b) money – from models with no money variables of any kind, to models in which all goods, services and factors of production have variable prices which affect the choices made by both suppliers and consumers.

The classification gives rise to seven or eight groups of models as shown in the table below. These draw upon a wide range of theoretical backgrounds and modelling methods, such that there are very few features in common across the whole set, and very significant differences even within the different groups.

Group	Group name	Main models in the group
1	Static adjustment models	DCM, PIRANDELLO, DSCMOD
2	Simpler models (simple/dynamics, limited/no money terms)	[2] QUANT, ITLUP [2A] MUSSA/ CubeLand
3	Systems Dynamics models	UDM, MARS
4	Microsimulation dynamic models	UrbanSim
5	Martin Centre models	TRANUS, MEPLAN, PECAS
6	Multi-level dynamic models	TIGRIS, DELTA, DELTA PFM
7	Urban SCGE models	RELU-TRAN, LUISA2

The report reviews the capabilities and limitations of these groups of models in relation to a long list of issues which might arise in forecasting for appraisal purposes. The general conclusions are all of the types of models considered can – by definition – meet the basic requirements of present TAG appraisal, but that for more elaborate requirements, including interaction with DLUHC appraisal or alternative forms of cost-benefit analysis, the models need to be at the more sophisticated end of the "money" dimension, with a fuller or complete representation of prices. On the "time" dimension, future appraisal could potentially be supported by models at any point; the most comprehensive models of urban economic equilibrium are found at the "static" end, but models towards the "dynamic" end offer practical advantages and at the same time are more intuitive and more readily related to empirical research into urban and regional change.

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ABBREVIATIONS

NB this list excludes the names of LUTI software packages and unique models that are the subject of this review, but includes the names of package applications that are mentioned as examples.

Abbreviation	Meaning
A2EM	access to economic mass
APPI	Assembly of Planning Policy Information
CGE	computable general equilibrium
CUE	computable urban equilibrium
CUPUM	Computers in Urban Planning and Urban Management (conference)
DfT	Department for Transport
DLUHC	Department for Levelling Up, Housing and Communities
DSC	David Simmonds Consultancy
EPSRC	Engineering and Physical Sciences Research Council
FLUTE	Forecasting Land-Use, Transport and the Economy (DELTA application for Sheffield City Region Mayoral Combined Authority)
HUMS	Household Urban Micro-Simulation model
IRPUD	Institut fuer Raumplanung, Univeritaet Dortmund (Institute for Spatial Planning, University of Dortmund)
ISGLUTI	International Study Group on Land-Use/Transport Interaction
LMS	Landelijk Model Systeem (Dutch National Transport Model)
LonLUTI	London Land-Use/Transport Interaction model (DELTA application for Transport for London)
LSTF	Local Sustainable Transport Fund (DfT programme 2011-2015)
LUMIT	Land-use modelling influenced by transport
LUTI	land-use/transport interaction
ME&P	Marcial Echenique & Partners
MSOA	middle-level super Output Area
NEG	New Economic Geography
NELUM	North of England Land-Use Model (UDM application for TfN)
NPV	Net present value
NTEM	National Trip End Model (Department for Transport)
ONS	Office for National Statistics
pcu	passenger car (equivalent) unit [traffic modelling]

Abbreviation	Meaning
R&D	research and development
RUM	random utility modelling
SCGE	spatial computable general equilibrium
SEELUM	South East Economy and Land Use Model (UDM application for Transport for the South-East)
STPR2	Strategic Transport Projects Review 2 (Transport Scotland)
TAG	Transport Appraisal Guidance (DfT)
TEE	transport economic efficiency
TELMoS	Transport/Economic/Land-use Model of Scotland (DELTA application for Transport Scotland; works with TMfS); various versions e.g. TELMoS05, TELMoS18
TEMPRO	Trip End Model Program (interface for NTEM) (Df)
TfN	Transport for the North
TFP	total factor productivity
TMfS	Transport Model for Scotland
TRRL	Transport and Road Research Laboratory (now TRL)
WEI	Wider economic impact(s) (in TAG)
WYCA	West Yorkshire Combined Authority

1 INTRODUCTION

1.1 Objectives

1.1.1 This Report has been prepared by Allanfield Consulting for the Department for Transport. The brief called for a review of the state-of-the-art in land-use/transport interaction (LUTI) modelling, as one of a series of reviews into alternative methods of supplementary economic modelling. The review was required to cover the following areas:

- theoretical underpinnings and applicability to transport appraisal;
- mechanics;
- data and input parameters;
- validation and output.

1.1.2 Through reviewing these it was expected to answer the following questions:

- How well are LUTI models suited for transport appraisal? What are the main limitations?
- What are the mechanisms used in LUTI models to calculate wider economic, and other wider social, benefits as in the UK government's Transport Analysis Guidance?
- How have other countries used LUTI model results in business cases?
- What is the likely cost of developing an LUTI for the UK?

1.1.3 These questions give the report slightly different objectives from the many previous reviews of LUTI modelling.

1.2 Report structure

1.2.1 The report is structured as follows.

1.2.2 Chapter 2 defines LUTI modelling and considers its relationship to transport modelling.

1.2.3 Chapter 3 introduces the range of concepts and techniques referred to in subsequent chapters. Drawing on this, Chapter 4 similarly introduces the range of theoretical bases to LUTI modelling.

1.2.4 Chapter 5 finally gets to grips with the models to be reviewed, explaining the set of models or packages considered, classifying them on key dimensions, and commenting briefly on their different theoretical backgrounds. A graphical comparison of the models is included which may be helpful in summarising some key characteristics and differences.

1.2.5 Chapter 5.12.11 sets out a list of requirements and issues for LUTI models to be used in transport appraisal, and chapter 7 discusses the models under review (in groups or where necessary individually) in relation to this list.

1.2.6 Chapter 8 draws out some conclusions in response to the questions set in the brief (see 1.1.2 above), and some additional comments.

1.2.7 The Appendices provide further information on the models reviewed and their backgrounds, with references, and some additional detailed material to support the main text.

1.3 Acknowledgements

1.3.1 The author is grateful to the Department for Transport for the opportunity to carry out this review, and in particular to the DfT staff who provided helpful comments on the draft report. Special thanks are due to all the modelling teams and individual experts who responded to requests for information and took part in discussions. The author remains solely responsible for any errors, omissions or misinterpretations.

2 THE RANGE OF MODELS REVIEWED

2.1 What constitutes a LUTI model?

2.1.1 This review is interested in models which

- represent activities using land in the different zones (or other units) of a real town, city or region, and
- will respond to specific changes in transport networks and services.

2.1.2 The first bullet excludes models that only exist for hypothetical places and models that represent places without any spatial detail.

2.1.3 The second bullet implies that we are interested in models which forecast what will happen as a result of specific changes (and may therefore help us to appraise them). Given that interest, the point deliberately **excludes** optimising models from this review. Optimising models seek to identify the scheme or policy (from a defined range of possibilities) that will produce the "best" result on one particular criterion[1]. Such analysis may have its place, but does not help with the standard appraisal question of assessing the merits or otherwise of a given proposal or comparing a given set of proposals. Note that the possible use of optimising (or normative) models is different from the use of standard non-optimising (or positive) models in an optimisation process; the latter is a normal, if challenging, use of the kinds of models reviewed in this report[2].

2.1.4 The second bullet also **excludes** models that work in terms of crow-fly distances or other abstractions, but allows us to **include**

- models which take account of only a single mode, or only consider passenger or goods transport, not both;
- full land-use/transport interaction (LUTI) modelling (i.e. where land-use both responds to and has effects on transport) and land-use modelling influenced by transport (LUMIT) where land-use is influenced by transport but land-use has no impact on transport.

2.1.5 The latter point is illustrated in

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[1] Optimising models have a long history as a niche activity within LUTI (and transport) modelling. For a fairly recent review see S Ezquerro and B Alonso (2017): Optimisation and Land Use–Transport Interaction Models. In Cordera, R, et al: *Land Use–Transport Interaction Models*. Taylor & Francis, Oxford.

[2] The issues of appraising interventions as interdependent parts of a wider programme, and the resulting need for "programmatic appraisal", were reviewed in Arup (2019): *Programmatic Appraisal: Stage 5 Report* [to DfT], available at https://assets.publishing.service.gov.uk/media/6163fd0ee90e07197718294c/programmatic-appraisal-stage-5-report.pdf.

- Figure 2-1, which illustrates the minimum components of full LUTI modelling, with two-way interaction between land-use and transport;
- Figure 2-2, which illustrates LUMIT modelling, with a one-way linkage from transport to land-use.

2.1.6 Note that the distinction between LUTI and LUMIT is one of how the land-use model is used rather than how it is designed. Any operational LUTI model system can be used in LUMIT mode, simply by switching off the land-use to transport linkage; in contrast, a system set up to operate as a LUMIT model might require significant additional development to add a land-use to transport link.

Figure 2-1 LUTI modelling: basic concept

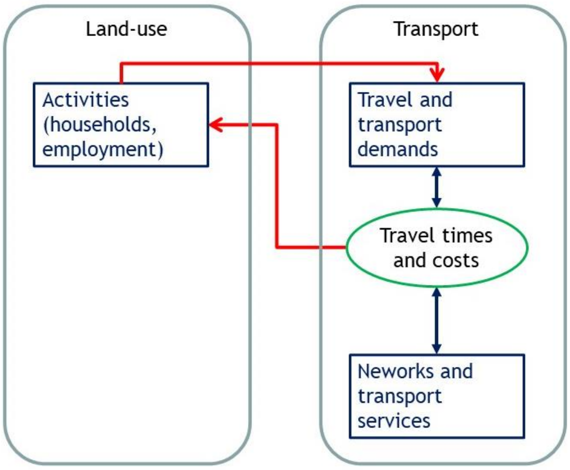
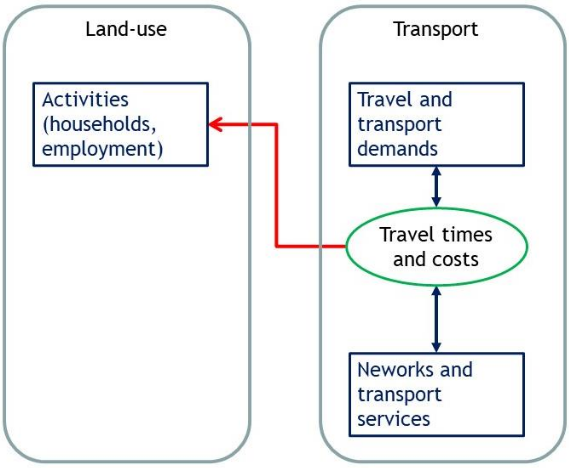


Figure 2-2 LUMIT modelling: basic concept



To avoid later confusion that might arise from the two-way connections in

2.1.7 Figure 2-1,, it should be emphasised that in most LUTI models, there is a time-lag of some kind between transport and land-use, so that the impacts of a transport change are not instantaneous. It is therefore exceptional, though not unknown, for a model to involve iteration between land-use and transport so as to find an overall equilibrium for one point in time.

2.1.8 We include both land-use/economic models that are integrated (more or less closely) with specific transport models as well as packages that are used with a range of transport models, including those which are normally used as "stand-alone" transport models.

2.1.9 It should also be recognized that most LUTI models consider the interactions between the land-using activities that generate the demands for transport (as shown in the diagrams above) and the land or floorspace in which those activities locate, as illustrated in Figure 2-3 below. Where these are not explicitly represented, it is necessary to consider what is implicitly assumed about them.

2.1.10 Such systems do not of course exist in isolation, but in wider economic and environmental contexts as illustrated in Figure 2-4. The interactions with the economy are mentioned at numerous points in this report, particularly with reference to scenarios. Explicit interactions with the environment are less common in LUTI modelling, and are highlighted where they are included.

Figure 2-3 LUTI modelling: more complete concept

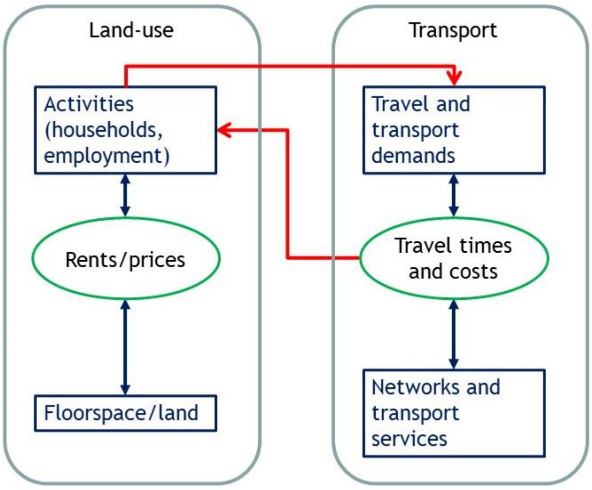
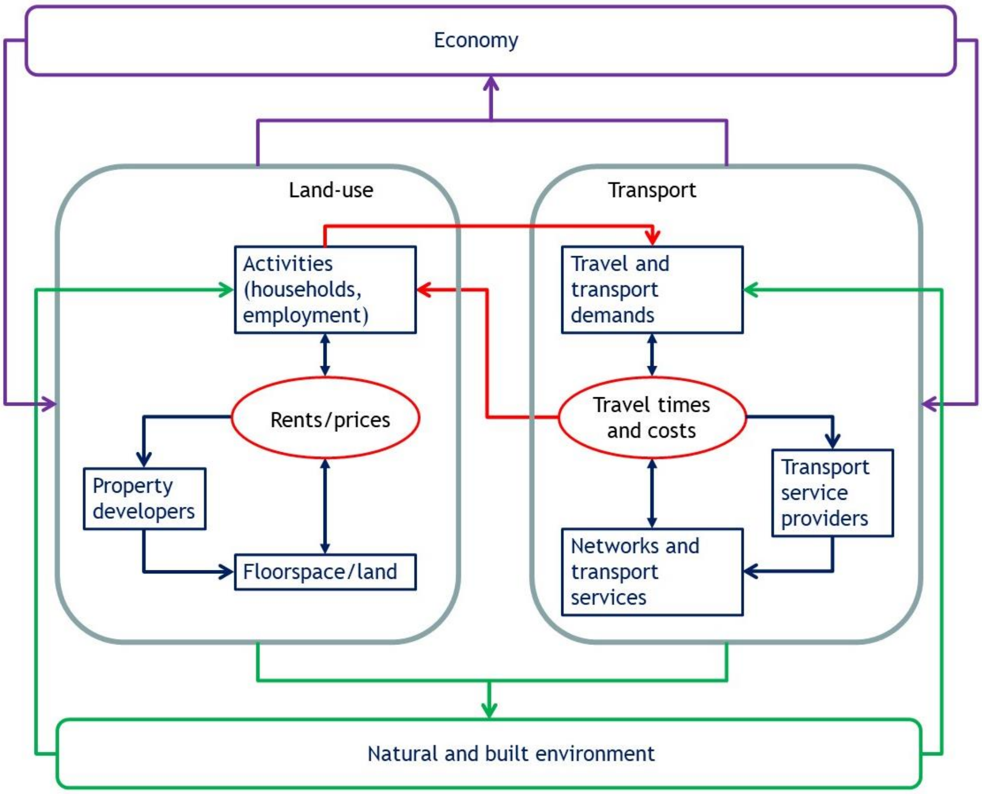


Figure 2-4 LUTI modelling: full concept



2.2 Models and modelling packages

2.2.1 The range of models considered extends from

- flexible software packages in which much of the detail is (has to be) written by the user in some form of macro language;
- moderately flexible packages offering a limited range of options (which can only be extended by the software supplier) – some of these options may be switched off/on by controls in the inputs or by setting relevant coefficients to zero/non-zero values;
- software which has been used in (at the extreme) only a single application by the developer, which may not offer any options at all (unless the source code is modified).

2.2.2 Note that in discussing “options” here we are referring to choices such as adding another variable to a location choice function; it is assumed that dimensions such as the number of zones and number of household types etc are readily changed for new applications, at least in cases where the software exists as a named package rather than as a one-off application. Such variability should not however be taken for granted e.g. it may be fairly trivial (at the start of implementing a new application) to change the number of household types that compete for housing, but not to introduce multiple types of housing (if that would require new functionality to calculate choice of housing type as well as choice of zone).

Similarly, the set of person types may be limited to pre-defined categories e.g. child, working-age, retired.

2.3 Relationship to transport models

2.3.1 This review is trying not to get into the details of the transport side of LUTI models. Most if not all of the models to be considered

- take matrices of generalised costs from a transport model, and
- can supply land-use data to that transport model, if it is a "four-stage" or similar one that incorporates trip generation and distribution or equivalent processes.

2.3.2 The review will however note

- which packages incorporate their own transport model, and whether this has to be used, and if so whether it is significantly different from a "standard" model
- whether the package requires, or can make use of, [a] any transport model outputs other than generalised costs (e.g. total traffic by zone) and/or [b] any other measures relating to potential interactions between places (e.g. contiguity, or straight-line distances).

2.3.3 One point that should be emphasised is that LUTI modelling requires complete matrices of generalised costs (and any other measures used) between all the zones "internal" to the model (i.e. all zones except external zones). This is the same as the requirement for agglomeration calculations, and different from the standard TEE calculations of user benefits which require generalised costs (or their components) only for zone pairs where those generalised costs may change as a result of the intervention being appraised. As in agglomeration calculations, intrazonal costs are important.

2.3.4 The criteria for transport model generalised cost outputs to provide a reliable basis for LUTI modelling are very much the same as for Wider Economic Impact calculations, and as such rather more rigorous than those for conventional transport appraisal[3].

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[3] The checklist of generalised cost requirements in TAG (section 6 of Unit A2.4) was based on a list of requirements for LUTI modelling – itself compiled on the basis of (sometimes painful) experience.

3 CONCEPTS, TERMINOLOGY AND TECHNIQUES

3.1 Introduction

3.1.1 This chapter gives brief explanations of some of the key concepts and terms, for two reasons. The first is to help readers who are unfamiliar with LUTI models. Also, some terms are used in different ways by different writers even within the field of LUTI modelling; a second purpose of this chapter is therefore to clarify how these terms are used in this report.

3.2 Land-use

3.2.1 An oddity of the types of "land-use modelling" considered here is that many of the models do not represent land at all. Often they represent floorspace, or in some cases a combination of floorspace for employment together with housing measured in dwellings or rooms. Some model both floorspace and the land on which it stands; others do not consider space at all, but only the activities located in zones, chiefly residence and employment.

3.2.2 For this review, a model counts as a "land-use model" if it outputs zonal forecasts of households or residents and employment, i.e. if it outputs the variables which are typically considered as "land-use" inputs to transport modelling.

3.2.3 If searching for material on land-use modelling it should be kept in mind that there are other forms of land-use modelling which focus on broad land-use categories such as agriculture, forest, wetland, urban, and on the transfers of land between these categories. These are not relevant here.

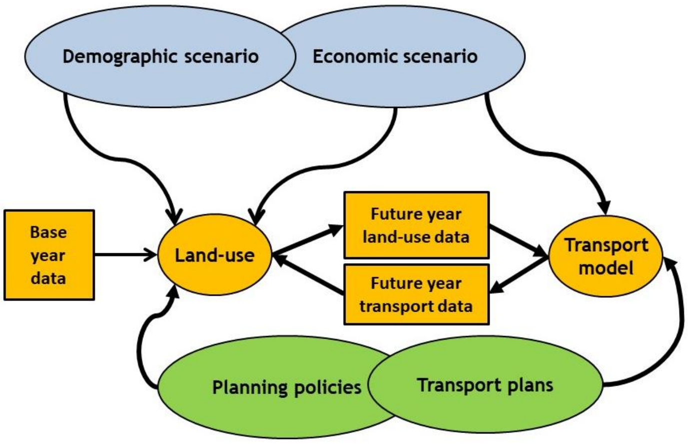
3.3 Scenarios, schemes, interventions etc

3.3.1 The general distinction here is that

- scenarios define the overall economic and demographic contexts of a particular set of forecasts, largely outside the control of the part of government for whom the LUTI modelling is being carried out
- strategies, schemes, plans, policies etc – in general "interventions" – define alternative courses of action that are to be considered within those scenarios.

3.3.2 Scenarios are typically defined for a modelled region or economy in total, whilst interventions are often very specific (e.g. a railway between two cities). Scenarios can therefore be considered as "top-down" inputs whilst interventions – such as transport proposals and land-use planning policies – are "bottom up" inputs, as illustrated in Figure 3-1.

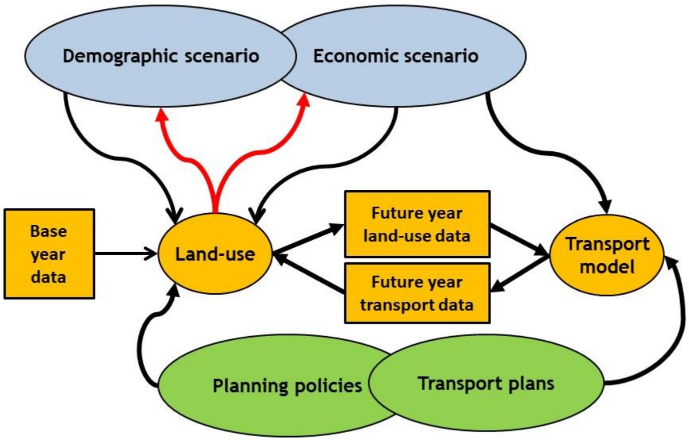
Figure 3-1 Scenarios and interventions as model inputs: fixed scenario



3.3.3 In some models, scenarios are very simply defined and can be input as control totals. In other cases, they are more complex, and may also need to be reproduced within the model calculations rather than being directly input. There are also relevant scenarios, such as DfT's NTEM, which specify very fine-grained local changes as well as overall totals. Some models can take these directly as inputs; others can be controlled so as to match them (this is considered later, in section 7.7).

3.3.4 A common reason for having the model reproduce aspects of the scenario, rather than taking it as a given input, is so that the model can adjust the scenario in response to the interventions (as illustrated by the red linkages in **Error! Not a valid bookmark self-reference.**). For example, rather than taking future GVA/worker by sector as an input, the model may calculate GVA/worker taking account of agglomeration effects which are modified by the interventions being tested. This may have further effects within the model as well as producing forecasts of total GVA which vary according to the intervention.

Figure 3-2 Scenarios and interventions as model inputs: variable scenario



3.3.5 Scenarios for LUTI modelling are typically based on economic and demographic forecasts prepared by others. In UK practice they are most often based on forecasts prepared by one of the major economic consultancies, who themselves draw on projections made by ONS and others. This raises the question of whether the assumptions made in the LUTI model are consistent with those that the external forecasting firm has made (perhaps implicitly) in producing the scenario[4]. This is considered further in section 7.7.

3.4 Base/Alternative Cases

3.4.1 At various points in this report we refer to estimating the benefits of an Alternative Case relative to a Base Case. This is standard; we mention it here only in order to point that this Base/Alternative Case distinction is not usually present in the modelling itself. In most cases, each model forecast is independent. In some cases, each model forecast is largely independent but certain key variables pivot about an initial “scenario-matching” run as described in the previous section.

3.5 Exogenous and endogenous

3.5.1 In this document, and in LUTI modelling discussion generally,

- exogenous means data input by the user;
- endogenous means data calculated by the model.

3.5.2 Without wishing to complicate that clear distinction, it is worth keeping in mind that a variable or set of variables may be exogenous at one point in a model and endogenous at another. For example, the numbers of households of each type living in each zone may be exogenous in the base year of a model that runs over time but endogenously forecast by the model for all subsequent years.

3.6 Static and dynamic

3.6.1 This report follows the usual LUTI practice of regarding models as static if they produce forecasts of certain variables as functions of the values of other variables at the same time, and as dynamic if they produce forecasts as functions of the values of other variables at a previous point in time, or as functions of the changes in other variables over a past period of time.

3.6.2 In practice, as will be seen, many models combine a mixture of static and dynamic sub-models, or have components which are mostly static with just one dynamic (i.e. time-lagged) variable.

3.7 Equilibrium and disequilibrium; iteration

3.7.1 “Equilibrium model” is used in this report to refer to a model in which two or more different variables, each influencing the other, are adjusted until each is consistent with the other, usually in order to meet a specific condition. A typical example is that numbers of households locating are influenced by the rents in different zones, and the rents are influenced by the number of households locating; the rents are

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[4] A related question is about consistency between the scenario and the Green Book assumptions. The default assumption in the Green Book is that project appraisal should assume full employment in the economy. The scenarios purchased from economic forecasting organizations do not necessarily satisfy that condition.

then adjusted until a situation is found in which the household locations are consistent with the rents and vice versa, and the household locations are consistent with the housing supply in each zone. Such a result, where all households are located and all housing is occupied, is described as “market clearing”.

3.7.2 As with the static/dynamic distinction, it will be seen that many models contain a mixture of equilibrium and other components. There may be multiple equilibrium components within the forecasting process for one year e.g. to represent the markets in different types of floorspace or different types of labour. In practice, each of these has to be solved by iteration – in effect, by repeated trial and error until the results are found to be in equilibrium, at least within a certain tolerance. Certain situations may not have an equilibrium situation e.g. a demographic scenario could introduce more households than could be accommodated given the modelled relationships between households and housing. If there is an equilibrium solution it is desirable, but may not be possible, to show that it is the one single unique solution to the model calculations.

3.7.3 Professor Anas has argued that many of the models in which adjustment processes work over time are also equilibrium models[5]. A summary of his classification is shown in Table 3-1 below. This is implicitly followed by some others e.g. Liu et al, whose recent review of market clearing mechanisms includes models in which prices or rents only adjust over time[6].

Table 3-1 Classification of equilibrium models: Anas

Source: Anas, op cit, summarised by the present author

#	Name	Description		
1	**Static equilibrium model**	No concept of time, no initial conditions. Equilibrium is simultaneous clearing of all modelled markets; there may be a unique equilibrium or multiple ones		
2	**Dynamic equilibrium model**	A model in which change over time in both exogenous and endogenous variables is recognized and represented. Agents may be myopic [responding only to past conditions or past changes] or act with perfect or imperfect foresight. May or may not involve lags in adjustment. Two sub-groups can be distinguished:	2A **Stationary dynamic equilibrium**	Exogenous variables not changing over time
			2B **Non-stationary dynamic equilibrium**	Exogenous variables are changing over time or model generates change over time even when exogenous variables are not changing
3	**Disequilibrium model**	Some prices are fixed; these markets must clear by other adjustments e.g. by changes to search or waiting times		

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[5] Anas, A (2013): Economics as the science for urban modelling. *Environment and Planning B*, vol 40, pp 955-958

[6] Yicong Liu, Eric J. Miller & Khandker Nurul Habib (2023): A review of the housing market-clearing process in integrated land-use and transport models. *Journal of Transport and Land Use*, vol 16 pp 335–359

3.7.4 It is not entirely clear from Table 3-1 whether, in Professor Anas' classification, a dynamic equilibrium model must be is one which **will** eventually clear the modelled markets, or whether it is sufficient that the model has effects which will give a tendency towards equilibrium (e.g. whether it is sufficient that demand responds negatively to price and supply positively, if they can). It is also unclear how the classification should apply if there are multiple equilibrium processes in the model. The present report therefore tries to spell out the nature of the equilibrium found wherever a model involves such a concept. It also allows for the possibility of a non-price equilibrium, i.e. an equilibrium where some other variable adjusts to clear a market or achieve a similar effect[7] (a category which Professor Anas would count as (3), a disequilibrium model).

3.8 Spatial interaction modelling

3.8.1 Spatial interaction modelling in the broad sense covers any modelling of the interactions between places (usually represented as discrete zones). A more particular sense is the design of land-use or economic models in which interactions are calculated first, and the quantity of something located is the sum of those interactions from each zone. For example, a number of models work on the basis that

- there is a given number of jobs in each zone;
- each job is associated with one household;
- taking the job location as given, each household decides where to live (given variables such as the housing supply in each possible residence zone, its rent or price, and the generalised costs of commuting from that home one to the given workplace);
- the number of households locating in each zone is then found by adding up the results of the location decisions made from each of the workplaces.

3.8.2 In the earlier review for SACTRA, this approach was identified as "interaction-location", because the interaction (between jobs and homes) is modelled first, and location is found by summing up afterwards. This contrasts with models in which location is forecast first (for jobs and for households) and interactions between them are conditional on the location of both.

3.9 Disaggregate modelling, microsimulation and stochastic variation

3.9.1 Most of the models considered in this review are aggregate in the sense that they directly calculate numbers of households, jobs etc locating in zones. (Moreover, their detailed calculations work in terms of real numbers, so locating fractions of households etc.) The exceptions are models, or parts of models, which work by

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[7] For example a land-use model where the equilibrium is found by reducing space per household, without modelling the price or rent changes through which this might come about: see Börjesson, M, R D Jonsson, S Berglund, P Almström (2014): Land-use impacts in transport appraisal. *Research in Transportation Economics* vol 47 pp 82-91.

disaggregate modelling methods, which forecast choices made by individual households, in one of two ways.

3.9.2 In **sample enumeration** methods, a weighted sample of individual households is used to represent the set of households making a particular choice, e.g. the set of households living in one zone who choose (first) whether to stay or to relocate. The sample may in fact be the same sample for every zone; the weights are calculated so that the weighted sample represents the number of households of each type (typically on a number of dimensions) in each zone. Discrete choices (e.g. move or stay) are modelled by choice models (in practice, random utility models) which forecast probabilities (e.g. 10% move, 90% stay) for each household in the sample. These probabilities are then applied to the weights: so if the weight on a particular household record is 45, then probabilities of 10% move, 90% stay are implemented as 4.5 becoming movers, and the remaining 40.5 households staying. The next choice (e.g. where to move) will then forecast the probability of choosing each destination, and those probabilities will be used to split up the 4.5 moving households. At the appropriate stage in the model operation these movers will be added to the numbers of households at their destinations by adding the number of movers to the sample weights there.

3.9.3 In **microsimulation** methods, a microdata set representing all the households in each zone is used as the base year starting point. In theory, observed data might be used; in practice, given the confidentiality restrictions on Census data and the lack of other complete datasets, the data has to be synthesized by expanding a sample, such as the Census Sample of Anonymised Records, to match the starting population[8]. The calculations of the model make a discrete choice for each record, so (following the same example as above) any one household will “decide” either to stay where it is or to move; and if it moves, it will move to one specific zone.

3.9.4 How microsimulation is used to represent choices, and the consequences, are discussed further in section 4.6.

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[8] One can think of such synthesis as taking a real sample of household data and expanding it to represent the population of a zone by duplicating records, whilst the synthesis to populate a sample enumeration model does so by calculating weights. In a simple case, one record would be given a weight of *N* for sample enumeration, and duplicated *N* times for microsimulation.

4 THEORETICAL BASES OF LUTI MODELLING

4.1 Introduction

4.1.1 This chapter aims to provide a brief summary of the various theoretical bases of LUTI modelling, as a means to understanding the differences between the various operational models which we will get to consider in subsequent chapters. We consider first the theoretical origins that are usually acknowledged in academic papers on LUTI modelling, and then consider the more specific question (as raised in the brief) about the relationship to New Economic Geography (NEG).

4.2 Theoretical bases of LUTI models

4.2.1 The present variety of LUTI models can usefully be explained as having developed from five different strands of work mostly going back to the 1960s or earlier:

- theoretical urban microeconomics;
- economic base modelling, and the older (1940s) idea of input-output modelling;
- Systems Dynamics (also known in this context as Urban Dynamics)
- microsimulation in social sciences (as already described in section 3.9, but giving rise to significantly different models)
- random utility modelling.

4.2.2 Different LUTI models show very different degrees of influence from the first four of these five. In contrast, random utility modelling has become almost ubiquitous, being used in nearly all LUTI models (as in most transport models). It is therefore convenient to consider random utility modelling first, before taking the others in turn.

4.3 Random utility modelling

4.3.1 Random utility modelling is mainly concerned with choices between discrete alternatives, such as zones, which makes it obviously relevant to practical LUTI modelling (it is in practice more or less synonymous with discrete choice modelling). Using a household’s choice of location as an example, the general propositions are that

- each household will choose the location that is “best” for them, given the set of alternatives on offer (i.e. where housing is available);
- “best” is defined by a utility function, which consists of
    - a known part which an analyst can quantify in a model (including for example variables such as the rent for housing in each zone, the

characteristics of the dwellings there, and the zone's accessibility to other places), plus

- a random part which cannot be measured: its distribution across the households in question has to be assumed.

4.3.2 The best location for any one household therefore depends partly on the measurable utilities, and partly on the random element. If the random element is very small, then nearly every household will choose the zone which appears best n their utility calculation. If the random element is very large, then households will largely ignore the measured variables, and will appear to locate at random – though more precisely, they are locating in response to variables, perceptions and preferences that the model does not represent. Part of the process of model estimation or fitting is to arrive at the distribution which best explains households' observed choices.

4.3.3 The mathematics of random utility modelling depend very much on the assumptions made about the distribution of the random elements. Under certain assumptions, the theory gives rise to the logit model, which is easily solved using a simple equation to find the probability of each alternative being chosen, given the measured utilities and a coefficient describing the distribution of the random elements. Software for estimating logit models is also readily available (i.e. to estimate the statistics describing the distribution of unknown terms in the model). Because they are practical to calculate, logit models are almost universally used in forecasting discrete choices both in mainstream transport models and in the LUTI modelling.

4.3.4 One particular feature of logit models is that, in addition to providing simple equations for forecasting the probability of each alternative being chosen in each choice situation, they also provide an equally simple measure of the expected average utility that will result. In the household location example used above, this will be the average utility of location for the group of households making the choice, inclusive of the effect of the unobserved random elements. This average measure, known as the logsum measure, is generally slightly better (higher utility) than a conventional average of the measured variables weighted by the proportions of households choosing each alternative.

4.3.5 An important application of logsum calculations in LUTI modelling is in calculating accessibility values. The expected average utility of a particular kind of trip from a given zone to destinations of the appropriate type (e.g. jobs, for work trips), provides a measure of accessibility from that zone to that type of destination. This kind of measure has a number of useful properties, e.g. improving transport to far-away destinations will appear as an improvement in accessibility (which it clearly is), or in the worst case as no change, in cases where a simple trip-weighted average generalised cost would show a worsening.

4.3.6 The description here is in terms of utility (more positive values are better), because that is in the name "random utility modelling", but the calculations can also be just as easily done in terms of generalised costs or disutilities (where more positive values are worse).

4.4 Urban microeconomics

4.4.1 This stream of work developed from considering the location of households in abstract and symmetrical cities with all employment located at a single central point on an otherwise infinite and featureless plain. The symmetry of the cities and the fact that they are uniform in all directions from the central point mean that they can be analysed using equations that describe location simply in terms of distance from the centre, and the results can be conveniently shown on graphs where the x-axis runs from the centre (x=0) to the edge of the urban area.

4.4.2 The most important contribution to this was the work of Alonso[9] looking at the competition between different land-uses (e.g. residential, office, industrial) and between different types of households (e.e.g by income). In relation to the housing markets, it highlights the trade-offs between rent, space per household and accessibility (to the centrally-located jobs) under differing income constraints. His analysis showed, for example, how it can come about that low-income households would pay high rents per unit of space in order to locate close to the centre (i.e. close to employment), but would be obliged to live at very high densities (very little space per household), whilst high-income households would locate at lower densities further from the centre[10].

4.4.3 This kind of budget-constrained trade-off between convenience of location (i.e. accessibility), quantity (and or quality) of housing and the rent or price of housing appears in some form in many LUTI models, but reapplied to an empirical situation where employment is found in many locations – and reapplied to firms' choices of location.

4.5 Input-output, economic base and SCGE modelling

4.5.1 The development of input-output modelling is generally credited to the work of Leontief in the 1940s. The basic idea is to analyse how much input of each kind of goods or services is required to produce one unit of output of each kind of goods or services, and the resulting total flows of goods and services between industrie. This gives a simple matrix-form model which can be used to examine the consequences of increased demand for any sector or sectors. Early applications included identifying where bottlenecks in the supply of inputs might limit the ability of American industry to supply military materials for the Second World War.

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[9] Alonso, W (1964): *Location and land use: toward a general theory of land rent*. Publications of the Joint Center for Urban Studies of the Massachusetts Institute of Technology and Harvard University. Harvard University Press, Cambridge, Mass.

[10] For brief introductions to Alonso's argument, see for example section 2.6 of de la Barra (1989 – reference in F.3), or pp95-99 of Bertaud, A (2018): *Order without design* (MIT Press, Cambridge Mass). There is an extensive literature stemming from or influenced by Alonso's work, including many theoretical models (i.e. applying to abstract cities) and applied numerical models that do not constitute LUTI models (e.g. NEDUM, which has been implemented as a model of the Paris region but considers only the housing market – see F Gusdorf and S Hallegatte (2007): *Compact or Spread-Out Cities: Urban Planning, Taxation, and the Vulnerability to Transportation Shocks*. Fondazione Eni Enrico Mattei Nota di Lavoro 17.2007; also in *Energy Policy*, vol 35, pp 4826-4838).

4.5.2 Input-output modelling generally considers one whole economy, with the nearest approach to any spatial aspect being the recognition of imports and exports. There are however two explicitly spatial versions:

- multi-regional input-output tables and models, in which either the trades between pairs of modelled regions are made explicit (making for a very large matrix) or trade between the regions is represented as exported to and imported from an "inter-regional trade pool" (with the total exports of each commodity to the pool matching the total imports of that commodity from it);
- spatial input-output modelling, in which the ratios of inputs to outputs are assumed uniform across regions, but there is a modelled choice of where inputs are obtained which is influenced by transport and other costs.

4.5.3 The latter approach is incorporated into a number of LUTI models.

4.5.4 A characteristic of input-output modelling is the identification of "final demand" which represent goods and services leaving the economy to be used for private or government consumption, for investment (e.g. the use of building materials in new construction), to be exported, or to be added to stocks. In input-output modelling, final demand is taken as exogenously defined. At the same time, incomes to households and revenues to government are calculated as rows of the input-output table. There are obvious linkages between the household incomes and government revenues going output of the model as rows near the foot of the table, and the households and government consumption expenditures coming into the model as columns on the right-hand side.

4.5.5 **Social accounting matrices** bring these linkages into the analysis, via a series of additional blocks. These provide the starting point for two further developments.

4.5.6 The first of these is **economic base modelling**, which simultaneously simplifies the social accounting matrix concept and gives it a spatial element by defining the modelled city region as having a given level and distribution of "basic employment" which supplies external (or exogenously defined) markets, and which - through its demands for labour - "generates" households, which in turn (through their demands for consumer goods and services) generate "service employment". This concept provided the basis for the Lowry model[11], which developed the first practical models of real cities (represented as systems of zones) from the idea of households locating around employment and service jobs locating around households. It used an iterative solution (comparable to that used in solving an input-output model) starting from the given quantity and location of basic employment to generate the whole city – sometimes called an "instant metropolis". Models based on this concept are still in evidence.

4.5.7 The second further development is that of **computable general equilibrium modelling, and** in this context particularly **spatial computable general equilibrium (SCGE) modelling.** Whereas economic base models are very simple, these models are very complex, allowing firms to vary the inputs they use,

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[11] Lowry, I S (1964): *A model of metropolis.* Rand Corporation, Santa Monica, Ca.

households to vary what they consume, and allowing for varying levels of saving with impacts on investment and productivity. These are the subject of a parallel review for DfT, so are not considered further here, except to note that elements of SCGE modelling appear in some of the models considered below.

4.6 Microsimulation

4.6.1 Microsimulation has already been noted as a technique; it is mentioned here under the broad heading of "theory" because it introduces the possibility of representing individual households, firms, or parcels of land. This can – at least in principle -

- reduce the need to group households and persons into defined categories or to divide space into zones, and
- avoid the restrictions of modelling actors' behaviour by means of equations and allow the modeller the freedom to represent (for example) different distributions of random elements, and/or to adopt more complex rule-based choice-making.

4.6.2 The first bullet point means for example that

- instead of classifying workers into full-time or part-time, which always poses a question of defining the boundary between "full" and "part", the model could work with the number of hours per week worked by each individual represented;
- zones could be replaced with individual parcels or grid cells each with a unique location and other specific characteristics (e.g. the uses of neighbouring parcels).

4.6.3 Considering the second point, a microsimulation model allows decisions of individual agents to be modelled in different ways, mainly

- using a random utility model (RUM) to predict the **probability** of the household choosing each possible destination zone; then randomly selecting which **will** be chosen, using a random choice which reflects that probability;
- explicitly adding a random component (representing for example individual variations in preferences) into the utilities of different alternatives, and choosing the best alternative[12]:;

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[12] The significance of explicitly adding a random component is that it allows the modeller to choose any distribution of random components which she considers appropriate. In contrast, RUMs as mentioned in the first bullet point of this list are limited to representations distributions which allow the resulting probabilities to be calculated with a single equation. For example, the basic logit model (which is by far the most common form of RUM) assumes that the random components take a Gumbel distribution (similar to the normal distribution) and are independently and identically distributed for each alternative in any one choice. With explicit random components in microsimulation, the modeller could choose different assumptions e.g. that car journey times may be faster or slower than calculated from network conditions, but that train journeys can only be equal to or slower than timetabled, never faster.

- using other rule-based choices with or without random elements – these can for example be based on series of decision rules rather than assuming a utility function in which variables are traded off against each other;
- using fixed probabilities based on previously observed data or other estimates. In the present context this kind of decision is relevant to aspects of the model which are taken as given – for example, fixed probabilities by age and sex may be used to represent the probabilities of individuals becoming a couple, or of a couple splitting up, which are fixed in order to represent a given demographic scenario. (There are models of household location – particularly in terms of migration – which work on fixed probabilities; they are not relevant here because they do not meet the essential requirement of responding to transport and related changes.)

4.6.4 Whilst rule-based choices allow a great deal of flexibility, one advantage of models based on a utility-maximising assumption is that there are well-established and readily available statistical methods for estimating these models, which can work efficiently on large and complex datasets and produce detailed statistics regarding goodness of fit, significance and other properties. This is not so much the case for rule-based models. Another advantage is that the properties of the model are well-understood and help to ensure intuitively logical and explicable results.

4.6.5 The forms of microsimulation involving random components or random choices are known as Monte Carlo simulation. A key consequence of Monte Carlo simulation is that the use of random numbers to make model decisions results in some stochastic (random) variation in the model results, even if the inputs to the model are exactly the same. Each forecast should be regarded as one case in a multi-dimensional distribution of results that may result from that one set of inputs. The significance of the stochastic variation depends on the scale at which the results are being considered: aggregate results for the whole of a large city (e.g. total car trip kilometres in a whole city) are likely to be very stable (the effect of stochastic variation will be negligible), whilst detailed local results will show much more variation.

4.6.6 Inconveniently for appraisal purposes, stochastic variation is more significant for the differences between two sets of results from different inputs than for a single set of inputs; with one Monte Carlo simulation each for a Base and an Alternative, it is impossible to say how much of the difference in results is due to the intervention being tested and how much due to the random effects. Where stochastic variation cannot be ignored, the theoretically correct treatment is to run the model many times and to average the results; this can be a significant practical issue with a large and time-consuming model.

4.6.7 An alternative for practical purposes is to adopt a method which ensures that the same random value is used whenever a specific agent makes a specific choice, starting from a specific situation in a specific year[13]; this eliminates stochastic

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[13] See for example Simmonds D, Feldman O, Christodoulou A, McDonald M (2011): *Latest developments in the SIMDELTA model: investigation of stochastic variation and development of disaggregate car ownership model.* Paper presented to the CUPUM Conference, Lake Louise, Alberta. A similar method has

variation between Base and Alternative, but (unless both are repeated multiple times) leaves the analysis using one pair of Base/Alternative forecasts out of the many that might be obtained, and not knowing how far these results are from the average of the distribution.

4.6.8 One further issue is implicit in the description above: the base data from which a microsimulation land-use model starts is nearly always itself the output of a Monte Carlo simulation process, and therefore represents only one sample from a potentially very large set of equally valid starting points. This seems to be very rarely considered. If the base data is highly controlled (e.g. the chosen sample of households is matched to observed Census data on many different variables) then the potential for stochastic variation may be very limited; but this ought to be tested rather than assumed.

4.6.9 Microsimulation has been used quite extensively in LUTI modelling practice in the USA (see Appendix E); in Europe, it has mainly been restricted to academic research.

4.7 Systems dynamics

4.7.1 Urban applications of systems dynamics, which itself is partly technique and partly theory, are characterised by emphasising feedback loops and change over time, in a continuing disequilibrium contrasting with the static equilibrium of urban economics and economic base modelling.

4.7.2 Presentations of systems dynamics models often imply that causal loop diagrams, and the feedback effects that such diagrams illustrate, are a unique strength of systems dynamics models. That is an exaggeration; there are other models that have many feedbacks and can be illustrated with causal loop diagrams – though it probably is true that only systems dynamics software allows models to be coded by drawing such diagrams directly into the computer[14].

4.7.3 "The technique of Systems Dynamics has its foundations in ideas from control engineering: the concept of system structure and behaviour is conceived in terms of levels of stocks which are progressively altered through time by rates of changes which are affected by various positive and negative feedbacks within the system of interest"[15]. The original development of Systems Dynamics was associated in particular with the work of Jay Forrester, and subsequently with the Club of Rome work on "The Limits to Growth" which attracted a great deal of attention in the 1970s.

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been implemented in connection with the PECAS microsimulation model of development (see Appendix F), and very probably by other teams working with Monte Carlo simulation.

[14] https://vensim.com/documentation/ref_sketch_editor.html

[15] pp 304-5 in Batty, M (1976) *Urban Modelling*. Cambridge University Press.

4.8 Relationship to theories of New Economic Geography

4.8.1 The DfT brief specifically asked to what extent existing LUTI models incorporate theories from New Economic Geography (NEG). Head and Mayer argue[16] that "five essential ingredients distinguish NEG models from other approaches to understanding the geography of economic activity". These are, in brief:

(1) increasing returns to scale internal to the firm;
(2) imperfect competition;
(3) trade costs;
(4) endogenous firm location;
(5) endogenous location of demand.

(The full text of the reference is quoted in the text box below.)

4.8.2 The five ingredients imply that some other ingredients of conventional economic modelling must already be in the mix: notably prices – otherwise increasing returns to scale will have no effect in the model.

4.8.3 The degrees to which different models represent any of these ingredients is considered in section 7.18.

Box 4:1 Ingredients of New Economic Geography

Source: Quoted from Head and Mayer, op cit, formatted by present author.

1 *Increasing returns to scale that are internal to the firm*	NEG models assume a fixed, indivisible amount of overhead required for each plant. NEG models *do not* assume any pure technological externalities that would lead directly to external scale economies.
2 *Imperfect competition*	With internal increasing returns, marginal costs are lower than average costs. Hence, one cannot assume perfect competition because firms would be unable to cover their costs. The vast majority of the literature goes on to assume a particular market structure and accompanying functional forms for demand: Dixit and Stiglitz' (1977) model of monopolistic competition.
3 *Trade costs*	The outputs and inputs used by firms are tradeable over distances but only by incurring costs. These costs are often assumed to be proportional to the value of the goods traded.
4 *Endogenous firm locations*	Firms enter and exit in response to profitability at each possible location. The assumption of increasing returns implies that firms have an incentive to select a single production site and serve most consumers at a distance. If plant-level fixed costs were negligible,

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[16] Keith Head, Thierry Mayer (2004): The empirics of agglomeration and trade. In Henderson, V and J-F Thisse: *Handbook of Regional and Urban Economics*, vol 4, pp.2609-2669. Elsevier, Amsterdam.

	the firm would replicate itself everywhere (a la McDonalds).
5 *Endogenous location of demand*	Expenditure in each region depends upon the location of firms. Two mechanisms for the mobility of demand have been proposed: (a) Mobile workers who consume where they work (Krugman, 1991a); (b) Firms that require the outputs of their sector as intermediate inputs (Krugman and Venables, 1995).
Ingredients 1–4 all appeared in the new trade literature, and in particular gave rise to the *home market effects* identified in Krugman (1980). With these assumptions, agglomeration can arise but only through the magnification of initial region size asymmetries. The key innovation of NEG relative to new trade [theory] is assumption 5. Without 5, symmetric initial conditions can be expected to lead to symmetric outcomes. With all five assumptions, initial symmetry can be broken and agglomerations can form through a process of circular causation.	

5 THE MODELS CONSIDERED

5.1 Introduction

5.1.1 This chapter will give a brief introduction to the key characteristics of each model or group of models. The objective is **not** to put models into a discrete classification such as static/dynamic but to discuss them in order based on their (approximate) positions on the time/dynamic dimensions.

5.1.2 One distinction that I think should be made is between "static adjustment" models, which require a complete forecast of land-use and transport as input and calculate how the land-use component (or some of it) will respond to a transport change, and the rest of the sample.

5.1.3 That said, it is important to note where other models require exogenous inputs e.g. some of the static models take the quantity and distribution of "basic employment" as given; others take household incomes as given.

5.2 The models considered

5.2.1 The models that form the main focus of this review, identified from a mixture of prior knowledge and search (online and by questions to individual experts), are listed in alphabetic order in Table 5-1. Inclusion in this list does not mean that the supplier/developer is necessarily offering either the model software or modelling services in the UK or any other market.

5.2.2 Models listed in italics are definitely no longer available, but are included either because they are part of the track record of other more recent models that are listed, or because they are relevant to other parts of this review. Specifically,

- MEPLAN[17] is no longer available but is listed and mentioned at various points because of its relatively widespread use in the past, and also because TRANUS and PECAS are still available as very similar models;
- IRPUD[18] was only ever used by its original developers but is listed and mentioned because of its importance as an influence on other models;

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[17] The MEPLAN package was sold to DfT after its development and support had been discontinued by WSP. It is currently used only as part of certain DfT models, though it is understood that it could potentially be revived.

[18] The IRPUD model for the Dortmund city region was developed over several decades by the late Professor Michael Wegener and colleagues at the University of Dortmund, and was run by that team (latterly as the consultancy Spiekermann & Wegener) for a long series of research projects. It was a major influence on other models including in particular DELTA, TIGRIS and UrbanSim.

- the other italicised names are mentioned as background (and because they have been prominent in previous reviews); their functionality is now available in other forms.

Table 5-1 Models considered

Note: inclusion in this list does not mean that the supplier/developer is necessarily offering either the model software or modelling services. Entries in italics: see text immediately above.

Name	Current [or last] supplier/developer (see note above)
CubeLand	Bentley Systems
DCM (Dynamic City Model)	Arup
DELTA	SYSTRA
DELTA PFM	SYSTRA
DSCMOD	*[DSC] – now available using selected components of DELTA software*
G-LUM	University of Texas at Austin
IRPUD	University of Dortmund/Spiekermann & Wegener
ITLUP	*[S.H. Putman Associates, USA] Now available as METROPILUS, TELUM and G-LUM*
LUISA2	Professor Ying Jin, University of Cambridge
MARS	Technical University of Vienna
MEPLAN	*[WSP]*
METROPILUS	S.H. Putman Associates, USA
MUSSA	*University of Chile – now available as CubeLand*
PECAS	HBA Specto Inc, Calgary (Alberta)
PIRANDELLO	Piron Consulting, France
QUANT	UCL
RELU-TRAN	Professor Alex Anas
STIT	Professor Pierluigi Coppola
TELUM	Federal Highway Administration (FHWA)
TIGRIS	Significance bv, Netherlands
TRANUS	Modelistica, Caracas
UDM	Steer Group
UrbanSim	UrbanSim Inc, USA

5.3 Classifying and comparing models

5.3.1 Rather than trying to classify models on the five or six different dimensions of theory introduced above, what seems more helpful is to discern the range of models in two main dimensions, these being

- their treatment of time, and

- their treatment of money.

5.3.2 The treatment of time ranges from

- models in which all of the relationships are simultaneous, i.e. the modelled city exists at one point in time with no past and no future, to
- models in which there are no simultaneous relationships except (possibly) those necessary for a minimal level of consistency at certain points in time (so that, for example, data passed to a transport model is coherent in terms of working persons by residence and workers by workplace).

5.3.3 A special case is that of "static adjustment" models which take a set of "base case" land-use and transport data as a given input for a future year, plus an "alternative" set of transport data, and calculate an "alternative" land-use forecast as a result of the changes in transport inputs.

5.3.4 The treatment of money ranges from

- models in which there are no money variables at all
- models in which all actors have revenue and expenditure streams (which must in some way balance), all transactions are influenced (for both buyers and sellers) by prices, and where the model as a whole demonstrates a "circular flow of money" (though not necessarily all the linkages through which money can circulate).

5.3.5 In between there are numerous models which have some but not all of the possible money variables, e.g. households have incomes which control how much they can spend on housing, but neither the source of incomes nor the receipt of rents is modelled (i.e. wages are not modelled as a cost to employers, not rents as income to landlords).

5.3.6 The resulting plot of models' treatments of time and money is shown in Figure 5-1 below. It is emphasised that

- the groups' positions on the two axes are only approximate;
- models within groups differ very significantly;
- in the case of more widely applied packages, not all their applications necessarily have exactly the same characteristics – especially where the package has been developed over several decades.

5.3.7 Table 5-2 names the groups; they are explained and their member models briefly characterised in the following sections.

5.3.8 The groups of models are then identified and explained below. We come back to their theoretical origins in section 5.10.4.

Figure 5-1 Models groups on approximate money/dynamics dimensions

Source: own analysis

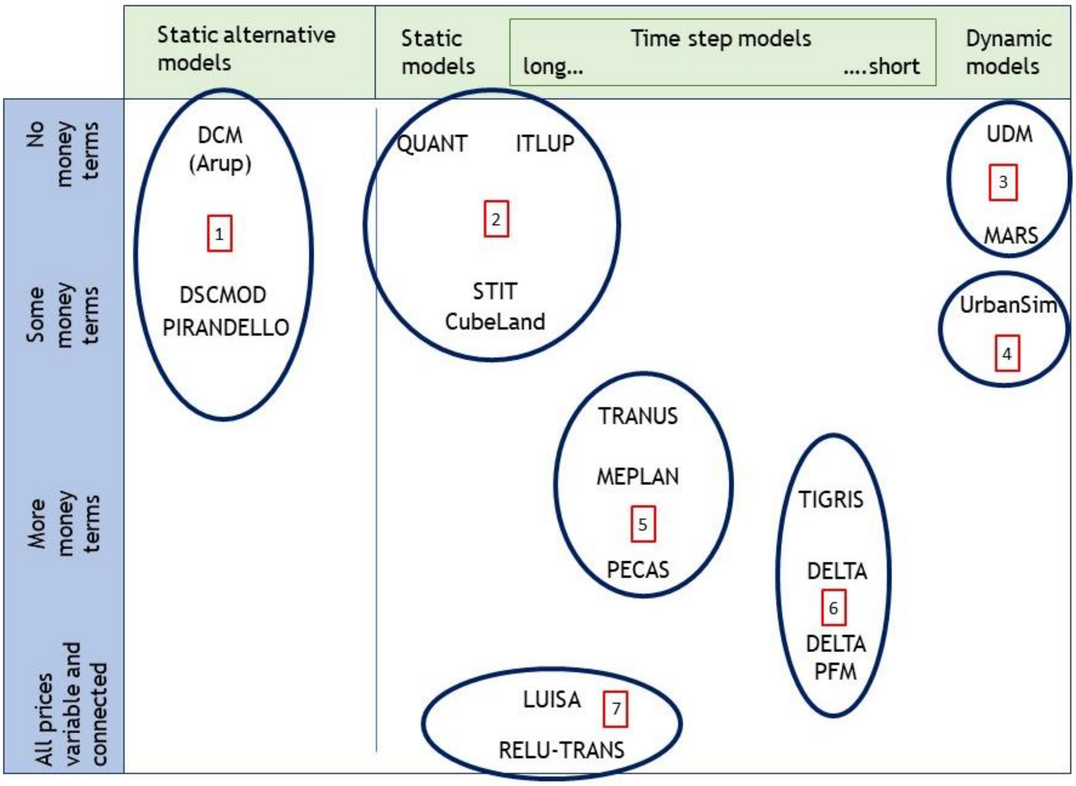

Table 5-2 Summary of model groups

Source: own analysis

Group	Group name	Main models in the group
1	Static adjustment models	DCM, PIRANDELLO, DSCMOD
2	Simpler models (simple or no dynamics, simple or no money terms)	QUANT, ITLUP, MUSSA/ CubeLand
3	Systems Dynamics models	UDM, MARS
4	Microsimulation dynamic models	UrbanSim
5	Martin Centre models	TRANUS, MEPLAN, PECAS
6	Multi-level dynamic models	TIGRIS, DELTA, DELTA PFM
7	Urban SCGE models	RELU-TRAN, LUISA2

5.4 Group 1: static adjustment models

5.4.1 Group 1 consists of a number of "static adjustment" models, i.e. those which read in Base Case land-use and transport data for one forecast year, plus transport data for an Alternative Case, and forecast the Alternative Case land-use that might result in that year. They therefore have no consideration of dynamic effects, and either no money terms or only housing/floorspace rents. They are arguably an intermediate form between single-equation spatial-economic models and LUTI models. Three examples are noted here, though there are probably others:

- the Dynamic City Model (DCM) recently developed in the UK by Arup;
- the PIRANDELLO model developed in France;
- the DSCMOD model developed by DSC in the UK in 1990-91.

5.4.2 Further details of these, with references, are given in Appendix A.

5.4.3 The DCM has been implemented as a UK-wide model at MSOA level, with a specific objective of meeting the requirements of land-use change for Wider Economic Impact calculations. It forecasts changes in residential location and employment location as a response to changes in accessibility resulting from transport changes, though without taking account of the interaction between the residential and employment effects It does not take any account of floorspace or land supply (though developments in this direction are planned); this can be interpreted as assuming that in any Alternative Case forecast, the supply of floorspace adjusts (by development, redevelopment or abandonment/demolition) so that rents and densities remain unchanged from the base case.

5.4.4 DSCMOD was very similar in design to DCM, but with the option to run the model with a fixed or exogenously changed floorspace stock as well as the option of assuming a perfectly elastic floorspace supply mechanism. Running with a fixed floorspace stock would reduce the relocation impacts as negative feedback effects would come about through rent changes. DSCMOD has probably not been used since the Borders Railway Reopening Study in 1999, but the functionality is available through appropriate application of the DELTA package.

5.4.5 PIRANDELLO was developed in the early 2000s as a model of Paris and the surrounding region (the Ile de France); it is not entirely clear where else it has been applied. It can be summarised as a further elaboration of the DCM and DSCMOD approach, with a more complex utility function for household relocation.

5.4.6 The distinguishing feature of the static adjustment models is that they read in all the forecast land-use data that they require for the Base Case (i.e., quite deliberately, the kind of data that is input to a transport model forecasting run), whereas all the models in the other Groups forecast their own Base Case. The static adjustment models are therefore convenient to use in situations where a lot of transport modelling has been done using a given scenario before land-use modelling is explicitly considered. However, at least if some of the models in the following models Groups can be constrained to match an exogenously given land-use forecast (e.g. NTEM) under certain conditions, and then to pivot about it if those conditions are changed; so they could also be used to look at the impact of transport change on a given land-use situation.

5.5 Group 2 models: limited or no dynamics, limited or no money variables

5.5.1 Group 2 consists of models which are either static or have simple step-wide dynamics in long steps (typically five years, sometimes 10) with few or limited money terms. Models within this group differ markedly in their detailed design, with some being far more sophisticated than others.

5.5.2 ITLUP is the original of a series of model packages developed in the USA, originally by Professor Stephen Putman in the 1970s. These models are essentially static spatial interaction models (see section 3.8), distributing households around workplaces and service jobs around households. There are no explicit rent or other mechanisms to limit the numbers of households or jobs locating in each zone.

5.5.3 QUANT is a very recent model in the same tradition developed at University College London. It is purely static, i.e. it does not involve any time-lagged effects or responses. It is of some interest in that (a) it is set up as a model of the whole of GB at MSOA level, and (b) it is designed to be operable by non-specialist users working via the internet.

5.5.4 Further details of these two models (and other comparable ones) are given in Appendix B, along with reference to some of the many similar models developed over the past 40 or 50 years.

5.5.5 CubeLand (see Appendix C) is unique within this category in that although it has few money variables, it incorporates a sophisticated application of Alonso's urban microeconomics theory. This design was developed from the 1990s by Professor Francisco Martínez, as the MUSSA model of Santiago de Chile. Some aspects of this microeconomic theory can be found in models of Groups 5, 6 and 7; what is unique about CubeLand/MUSSA is that not only do potential occupiers of space compete for space, but there is also an explicit hypothesis that this occurs through an auction-like process in which landlords accept the highest rents that potential occupiers bid for each kind of property in each zone. (In Groups 5, 6 and 7, either no explicit hypotheses about landlords are set out at all, or their responses are limited to choosing between letting floorspace at the going rent or keeping it vacant.)

5.5.6 All of the models in this group are aggregate in nature. In the CubeLand case, this means for example that the "best bid" rents that landlords accept are calculated from the distribution of bids offered by potential tenants[19], not by choosing the individual best bid from a list.

5.6 Group 3: Systems Dynamics models

5.6.1 Group 3 consists of models which are based primarily on considerations of dynamics, implemented in aggregate form in Systems Dynamics software. They work in one-year steps but make use of "time steps" or "time slices" to obtain some feedback effects within each year – but unlike most of the other models considered, these feedbacks do **not** involve any iterative calculations seeking to converge on an equilibrium solution.

5.6.2 The two models identified in this category are the UDM and MARS packages. Further details are given in Appendix D. Both are defined very much in the usual systems dynamics terms of stocks, flows, and feedback loops, with limited documentation (none, in the UDM case) in terms of mathematical equations. Responses are defined largely in terms of lookup tables, though the MARS model

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[19] Specifically, the logsum (expected maximum) of the bids. See around equation (7) in F Martínez and P Donoso (2010): The MUSSA II land use auction equilibrium model, in F Pagliara, J Preston, D Simmonds (eds): *Residential location choice - models and applications*. Springer, Berlin.

does involve some logit models. UDM does not involve any money variables; MARS has a simple rent variable which changes over time (as in Group 4). Neither involves any iterative calculations within any one year or period, equilibrium (unless it results from a lengthy period without any exogenous change) being anathema to systems dynamics models.

5.7 Group 4 models: micro-dynamic models

5.7.1 Group 4 also consists of models which are strongly influenced by dynamic considerations but which are implemented in highly disaggregate forms using microsimulation. Again, these do **not** use iterative calculations to converge on an equilibrium solution.

5.7.2 This group is currently represented in practice, as distinct from research, by just one modelling package, UrbanSim, though other packages may be under development, and a number of past models have been either wholly or partially microsimulation-based. The main UK example of a fully microsimulation land-use model was MASTER, which was applied to Leeds and to London[20]; the ILUMASS model was a particularly ambitious German example[21]. There is also the long-running ILUTE research project in Canada[22]. Models making partial use of microsimulation in LUTI modelling have included

- the IRPUD model of Dortmund, a long-running research project (see Appendix **Error! Reference source not found.**) which was a major influence on all the other models mentioned in this group and in Group 6, and
- SimDELTA, a much shorter experiment in using microsimulation for the household choice processes in the DELTA (Group 6) model, carried out for DfT (see **Error! Reference source not found.**).

5.7.3 Further details are given in Appendix E. Apart from some of the American UrbanSim applications, these models have been used only for research purposes.

5.8 Group 5: Martin Centre models

5.8.1 Group 5 consists mainly of three modelling packages with a common approach, all having origins in research carried out at the University of Cambridge Martin Centre for Architectural and Urban Studies – though most of their development and application since the mid-1970s has taken place in various consultancy contexts.

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[20] See references in Table E-1, page 121.

[21] For ILUMASS and the Dortmund group's subsequent retreat from all-micro modelling see (1) Moeckel, R, B Schwarze, K Spiekermann, and M Wegener (2007): *Microsimulation for integrated urban modelling*. Paper presented to CUPUM, Foz do Iguaçu, Brazil; (2) Spiekermann, K, and M Wegener M (2011): From Macro to Micro - How much is too much? *Transport Reviews*.

[22] See for example Chingcuanco, F and E J Miller (2018): The ILUTE Demographic Microsimulation Model for the Greater Toronto-Hamilton Area: Current Operational Status and Historical Validation. In J-C Thill, S Dragicevic (eds): *GeoComputational Research on Regional Systems*. Springer, Berlin.

5.8.2 The key features of these models are the integration of Alonso-type urban economics in terms of the trade-off between accessibility, space standards and cost of location, with an economic base approach to the total quantities of activity in the urban system. They are all largely static equilibrium models, albeit with some components which calculate change over time. Typically, the static components are run at five-year intervals. Like other static models they are largely calibrated on base-year data.

5.8.3 The first model to combine these elements was developed for Bilbao (Basque Country)[23]. It was not at the time a named software package, but was used for a number of other applications and as the “MEP model” in the first phase of ISGLUTI[24]. It was developed into the first version of the MEPLAN package circa 1985; the very similar TRANUS package was in operation by 1984[25]. Support for MEPLAN ceased in the 2010s, and the only remaining use of (part of) the software is in one of the DfT models. TRANUS remains in active use with support from its developers, Modelistica (Venezuela); versions are available for free download both as standalone software and as a plug-in to Q-GIS; UK applications have mostly been for academic purposes[26].

5.8.4 PECAS was originally developed by HBA Specto in the late 1990s and early 2000s, drawing on the ideas and experience of MEPLAN and TRANUS but seeking to address a number of their theoretical shortcomings[27]. The refinements it has offered (some of which may since have been matched in TRANUS) include moving away from the original MEPLAN/TRANUS design of a fixed quantity of “basic employment” located by the incremental models (i.e. between time periods, and hence outside the equilibrium process) to an explicit representation of exports which are endogenously located by the model, and which are elastic in quantity with respect to prices; and more flexible relationships between sectors (moving away from the fixed coefficients of the input-output model towards a system of production functions). The treatment of imports is also elastic with respect to prices, meaning that the size of the economy in the modelled region is sensitive to varying levels of “leakage” as well as the competitiveness of exports.

5.8.5 A separate feature of PECAS is that the model of floorspace development has in some cases been implemented as a parcel-based microsimulation model, thus addressing the perennial problem of the variability of parcels or sites within almost any zone of any city. This gives PECAS the potential to combine the fine spatial detail of the Group 4 approach (e.g. UrbanSim) with some of the more

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[23] Geraldes, P, M H Echenique, I N Williams (1978): *A spatial economic model for Bilbao.* Proceedings of the PTRC Summer Annual Meeting, PTRC, London.

[24] see Appendix J

[25] de la Barra, T (1994): From theory to practice: the experience in Venezuela. *Environment and Planning B,* vol 21 pp 611-618.

[26] Most recently Sarri P, Tzouras P G, Tsigdinos S, Kaparias I, and Kepaptsoglou K (2024): Incorporating Land Use and Transport Interaction Models to Evaluate Active Mobility Measures and Interventions in Urban Areas: A case study in Southampton, UK. *Sustainable Cities and Society* vol 105.

[27] https://www.hbaspecto.com/products/pecas/pecas_history/

comprehensive and responsive treatment of the economy seen in Group 6 and in particular in Group 7 (below).

5.9 Group 6 models: multi-level dynamic models

5.9.1 Group 6 consists of two models that whose common features are first a focus on dynamics, strongly influenced by the IRPUD model (see 5.7 above, and Appendix **Error! Reference source not found.**), and secondly a multi-level spatial structure.

5.9.2 The first of these, TIGRIS, is a national model of the Netherlands; it does not appear to have been implemented elsewhere or used to build more detailed models for any part of the Netherlands, though the model design appears reasonably portable. The second is the DELTA package, which has been quite widely applied in the UK, and has also been used in France, South Korea and New Zealand. TIGRIS was developed for agencies of the Dutch government. DELTA was developed privately in the mid-1990s but has been used for a range of national and local governments.

5.9.3 Along with other dynamics-focussed models (IRPUD and UrbanSim) these models have a modular structure in which different processes of change are modelled in turn.

5.9.4 The TIGRIS model was designed to extend the established Dutch National Model System (LMS) from being a standalone transport model into a LUTI system, using the same methods of disaggregate choice modelling that were very successfully pioneered in the LMS. The overall design is broadly based on that of IRPUD, but extended to national scale; it was designed from the outset to work with a two-level spatial system, consisting of 40 regions and 1308 zones. Both demographic and economic scenarios are externally specified.

5.9.5 DELTA was originally designed to provide a more practical (and more portable) IRPUD-like dynamic model that would also use what were considered the best aspects of the earlier Martin Centre models i.e. the modelling of floorspace markets based on Alonso-type microeconomics, with rents adjusting so as to clear the market in each period. The key change from the Martin Centre in the modelling of markets was to model the clearing of the market for the subset of households (or jobs) and floorspace who are active in the market in each period, rather than for the whole market. The original version of DELTA was, like TIGRIS, designed to work with exogenously specified demographic and economic scenarios, though the demographic scenario is applied by modelling household transitions calibrated to reproduce the required scenario rather than by imposing control totals.

5.9.6 A further theme in the development of DELTA was the desire to develop a modelling approach that could draw upon the extensive range of empirical work in urban economics, urban geography and other disciplines researching different ways in which cities and economies change over time - the kinds of changes that urban models are attempting to forecast. (Most earlier urban modelling existed very much in isolation, and the literature of urban modelling gave no hint that urban geography or urban economics even existed as disciplines.) The developers of TIGRIS took an opposite but complementary approach, being designed so that it could be calibrated on obtainable data, but using data on changes over time analysed using methods that themselves represent a contribution to the wider literature rather than just to the implementation of a specific model.

5.9.7 A major divergence between DELTA and TIGRIS was the addition of a "regional economic model" level to DELTA in the late 1990s. The empirical literature shows that different if related variables affect household moves over short, medium and long distances, and that there are similar differences between firms' location choices between cities and their choices within cities. A higher-level zone system was therefore added to the DELTA design, with units that have at different times been called areas, sub-regions or (currently) macrozones, each containing one or a number of the basic model zones. The regional economic model consisted of a spatial input-output model (similar to those in the Martin Centre models) but with the addition of an "investment model" which changes the relative capacity of each sector in each macrozone over time; these changes in capacity have an important influence on the working of the spatial input-output model and hence on the location of production and employment[28]. This means that the spatial input-output model mainly represents the short-term effects whilst the investment model, which has considerable inertia and long time-lags, represents longer-term changes. Similarly, a migration model allows for the movement of households over longer distances, with the original model retained to represent shorter-distance moves more strongly influenced by housing availability and rents.

5.9.8 TIGRIS and DELTA seem to remain distinct among LUTI models in seeking to represent inter-regional and intra-regional economic and demographic effects in one model, with two-way linkages between the levels[29, 30]. (PECAS has two levels with two-way interaction, but between zones and the parcel-level lower layer, and only for changes in the building stock). This feature is obviously irrelevant to models which are applied only to single city regions, but among the other models that are used to represent large study regions (e.g. QUANT and LUISA for the whole of GB, PECAS for statewide models in the USA) the lack of attention to differences in effects between intra-city and inter-city choices is curious, given it has had considerable attention in research.

5.9.9 The DELTA PFM version is a prototype model developed as a variant of the Highways England Economy Model. The PFM used a modified version of the

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[28] See Simmonds D and O Feldman (2013): Modelling the economic impacts of transport changes: experience and issues. In F Pagliara et al (eds): *Employment location in cities and regions.* Springer, Berlin.

[29] DELTA also has a third level which is used to interface to transport models with non-matching zone systems.

[30] The available material on TIGRIS is not very clear about which aspects of the model work at which level, but the block diagrams (Figure 5-1, p87 in Zondag 2007, or Fig 4.1, p60 in de Graaff and Zondag 2013) show that it is the labour market modelling i.e. the interaction of labour market demand and workforce supply, that operates at the upper level (though this is labelled as 40 COROP regions in the former and municipalities (342) in the latter – presumably due to different version). The labour market module of TIGRIS takes in the national scenario for numbers of jobs and a range of upper-level-zonal inputs including population and floorspace data, and outputs jobs and number of residents in work by upper-level zone (see Zondag, 2007, Figure 5-11 p 126). The paper by de Graaff and Zondag (2013, p61) explains that the residential location choice is a hierarchical logit choice of region and location within region (though that is in the housing market module which is shown in the corresponding diagram as being at the lower level).

regional economic model which moved from fixed input-output coefficients to a system of production functions comparable to those in PECAS, meaning that changes in transport cost (or planning policy) could potentially influence the proportions in which sectors use labour, space and intermediate goods and services, and the overall size of the economy. Work was carried out (in a separate exercise) on replacing DELTA's own regional economic model with an existing national SCGE integrated into the LUTI system, though this design did not even get to a working prototype (for resource, not modelling reasons). Both projects indicated that further integration of or with SCGE modelling at the upper (national) level of a LUTI model is possible and (in terms of model scope) desirable[31], though there are many detailed issues to resolve.

5.9.10 Further details are given in Appendix G.

5.10 Group 7: urban SCGE models

5.10.1 Group 7 consists of the "urban SCGE" models, which have fully economic representations of the urban economy in that **all** quantities have prices and the demands for those quantities respond to prices; for most variables, supply also varies in response to prices. These models involve iteration to complex equilibrium situations; they may be entirely static or can be run at intervals (e.g. every fifth year) with floorspace supply changing over time (as seen for PECAS in Group 5). The term "Computable Urban Equilibrium" model (CUE) is also used for this group.

5.10.2 As applications of SCGE methods, they are expected also to feature in the parallel review of SCGE models, so are treated more briefly here. The key example is the RELU-TRAN model, which has been applied to Chicago and Paris; the subsidiary example is the very similar LUISA model of the UK.

5.10.3 One characteristic of these models is that they can assume perfect foresight among all the actors involved, though it is not clear how within the design or operation of the model this is implemented[32]. This question is left to the SCGE review. All of the other models considered in this LUTI review are more or less myopic, in the sense that actors have – at most – perfect knowledge of the present situation, or of past and present, but no foresight. In many of the dynamic models actors have very limited knowledge of the present situation, only of the recent past.

5.10.4 Further details are given in Appendix H.

5.11 Theoretical backgrounds and technical approachs: summary

5.11.1 Chapter 4 identified a number of major theoretical influences on LUTI modelling. Of these, random utility modelling is virtually ubiquitous in current models, except

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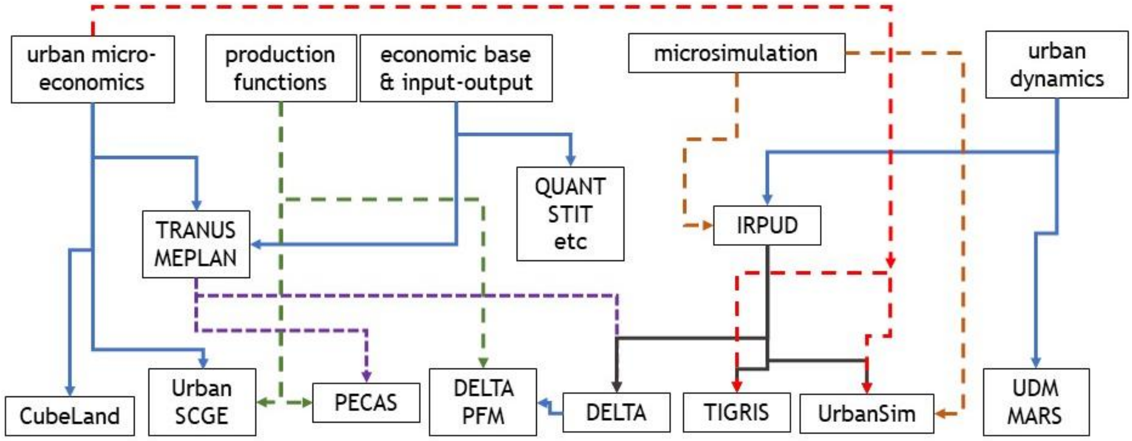
[31] The arguments (with an illustration of some PFM results) are summarised in Atter, L, D Bahyl, C Dosad, L Lees, D Simmonds (2018): *Understanding the real economy impacts of transport and planning strategies*. Presentation to European Transport Conference, Dublin.

[32] More precisely this is asserted in one of the RELU-TRAN papers; since the design of LUISA appears to be identical, it presumably applies to LUISA too if LUISA is solved in the same way.

possibly for the UDM[33]. The influence of the other streams of theory can be seen to different degrees in each of the range of current models and modelling packages, and this is illustrated to some extent in Figure 5-2 below (the economic component has been split to separate the economic base and input-output concepts, which imply fixed inputs to sectors, from the production function concept which implies variable inputs). The figure illustrates that there has been little convergence in urban modelling practice: the more recent and most active models, those in the bottom row, have little in common, especially between those at the outer ends of the row.

Figure 5-2 Theoretical origins of LUTI models

Note: this is a selective picture of the main influences and connections. Other near-ubiquitous influences include random utility modelling (nearly always as logit models) which is used in all the named models shown, except possibly UDM. Colours and dashing are arbitrary and intended only to distinguish between different linkages.



5.11.2 Whilst all the models in the bottom row of Figure 5-2 have a fair claim to be “state of the art” in their particular branch of modelling, the diagram illustrates their variety and shows that there is no single “state of the art”;. Similarly, no one model can claim to be the typical “state of practice” in the way that the fairly conventional “four-stage” aggregate transport model is the typical “state of practice”, at least in the UK.

5.11.3 A further consequence is that “land-use modelling” or “LUTI modelling” has not developed as a profession to the degree that “transport modelling” has; professionals working in LUTI modelling have tended to stay with one firm or model, or to move out of the field altogether – though there are signs that this is starting to change, with “LUTI modeller” starting to appear as a job title in client organizations as well as within the specialist firms.

5.11.4 As a practical point for the present review, it also needs to be kept in mind that some of the packages have been in existence for several decades, and some have been very significantly modified or extended in that time – sometimes in response

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[33] The uncertainty is because the lookup tables and other functions used in the UDM **might** approximate to logit models.

to new ideas and requirements, sometimes in response to identified problems or limitations. Individual applications of a single package may also have experienced repeated changes and enhancements; not all applications use all the features of the package they are built in. The descriptions of models in this or any other review must therefore try to draw out essential characteristics and to indicate the range of options available; this makes it more difficult to draw conclusions.

5.12 Model comparisons

5.12.1 The figures starting on page 47 attempt to give a visual impression of how different models compare in terms of

- their coverage of key variables;
- the linkages between these variables – which affect which;
- whether those linkages have immediate or time-lagged effects; and
- if linkages are immediate, whether an equilibrium of some kind if found between different effects.

5.12.2 The same variables are listed as rows and columns; each row considers a variable as an influence, and each column considers it being influenced. Figure 5-3 provides a key.

5.12.3 With reference to coverage:

- the diagrams do not show all relevant variables in all cases, and do not attempt to show **how** the influences work;
- variables that are not explicit in the model are greyed out across their row and down their column. Note that this may mean they are implicitly constant, rather than that they have no effect. (In the case of car ownership, it may be that it is explicitly forecast in an associated transport model.) A row can only be completely unshaded and empty if a variable is modelled but doesn’t affect any of the other tabulated variables, and a column can only be completely unshaded and empty if a variable is modelled but completely unaffected by any of the other tabulated variables.

5.12.4 With respect to linkages:

- where one variable influences another immediately (at the same point in time), the relevant cell is shaded green; where there is a delayed lag, it is shaded blue. (If both apply (i.e. where there are two distinct linkages) the green is shown.) Note that where a model is incremental over time, i.e. a variable remains the same over time unless something happens to change it, there will be blue cells on the diagonal of the diagram;
- where one variable influences another through an accessibility measure or other variable reflecting transport times/costs, the cell is also outlined in red – so the distribution of red outlines shows where transport cost effects enter the model. (Other transport effects, e.g. the impact of noise, pollution etc on zonal attractiveness, are not shown as they are rarely modelled);

- only direct influences are shown; it should be possible to trace indirect influences from column to row. In many cases, a blank cell means there is an indirect influence, unless the column variable is identified as exogenous.

5.12.5 Where a variable is normally partly exogenous in quantity and location, the row and column heading include a light brown square symbol. If a variable is wholly exogenous, the whole column is shaded light brown.

5.12.6 Where a variable is normally constrained by planning policy inputs, the column heading is outlined in purple. (In at least one case these inputs can be made endogenous to forecast context-specific policy changes in the long term; this is not distinguished.)

5.12.7 Planning policies are effectively exogenous inputs e.g. a model run to test “what if a new town is built in location *L*” could be regarded as a planning policy or an exogenous floorspace input. Most of the models are probably amenable to some values being fixed or manipulated in order to represent “what if…” tests.

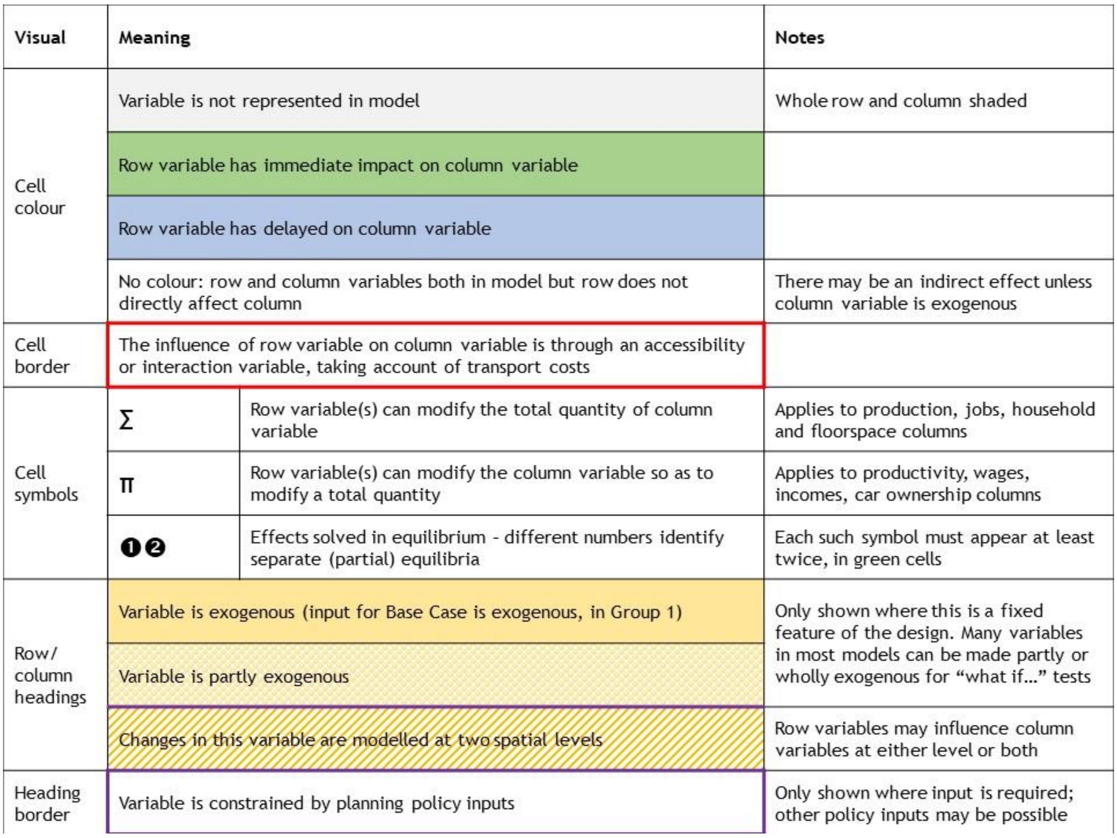
5.12.8 No attempt has been made to show which models may leave space or labour unused (i.e. vacancy or unemployment)

5.12.9 A sigma symbol (Σ) is used to show where a variable (or group of variables) can directly modify the model-wide total of one of the key “quantity” variables. A pi symbol (π) is used where a variable (or group of variables) can indirectly modify one of the “ratio” variables in a way that may change an overall quantity (e.g. a change in productivity may lead to a change in model total GVA).

5.12.10 The diagrams should therefore help to illustrate

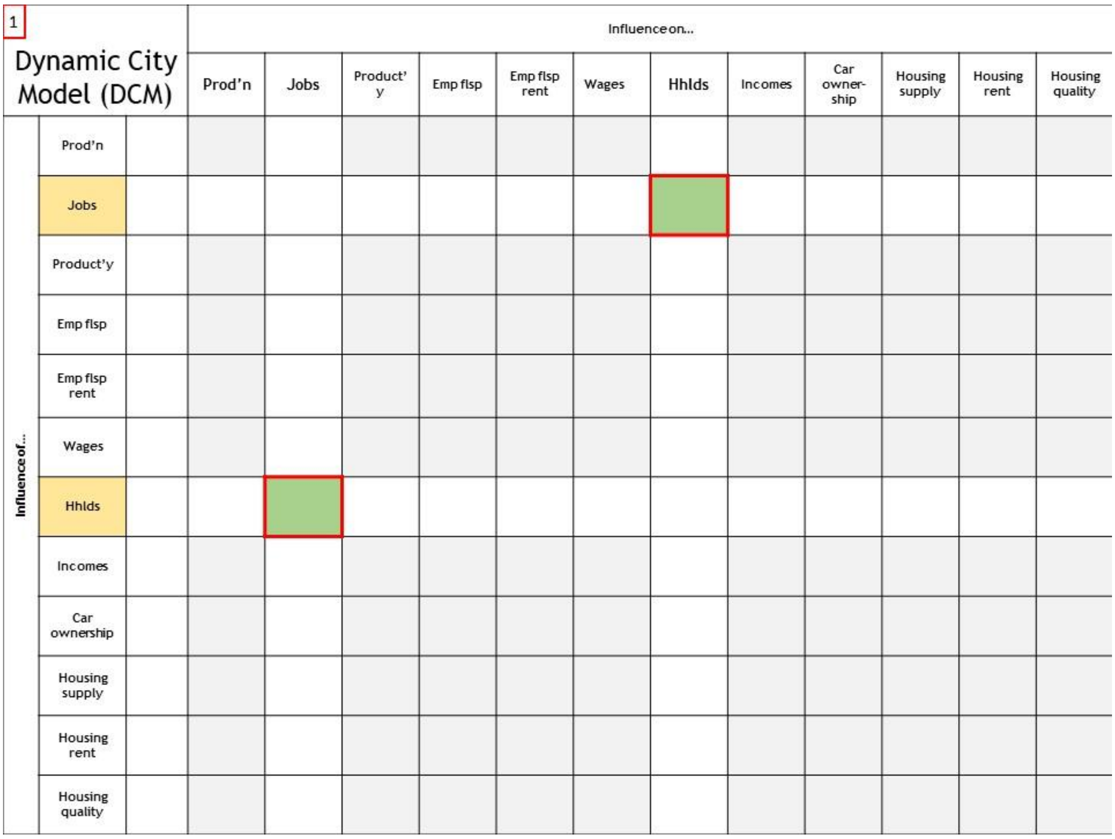
- which models are more limited in scope: more grey cells;
- which have more simultaneous linkages: more green cells;
- which of those have more equilibrium solutions: numbered green cells;
- which have more time-lagged linkages: more blue cells;
- which inputs are exogenous: yellow shading to left;
- which variables are constrained by planning policy inputs: purple outline at top;
- which linkages are affected by transport: red outline (note that given our definition of LUTI models, these consistently include the linkage from job numbers/location to households and vice versa, with some other cases in some models);
- which variables are modelled at two or more levels of spatial detail in which models: orange hatching at top;
- where whole-model totals of the main quantity variables (production, jobs, households, floorspace) may be changed (sigma signs in relevant cells), or ratio variables which imply key quantities (GVA, incomes, cars owned) may be changed (pi signs in relevant cells). If neither symbol occurs in a column, the total is fixed by the inputs defining the modelled scenario (which may be an input total, or more complex).

Figure 5-3 Key to model comparison graphics



Visual	Meaning	Notes
Cell colour	Variable is not represented in model	Whole row and column shaded
	Row variable has immediate impact on column variable	
	Row variable has delayed on column variable	
	No colour: row and column variables both in model but row does not directly affect column	There may be an indirect effect unless column variable is exogenous
Cell border	The influence of row variable on column variable is through an accessibility or interaction variable, taking account of transport costs	
Cell symbols	Σ Row variable(s) can modify the total quantity of column variable	Applies to production, jobs, household and floorspace columns
	π Row variable(s) can modify the column variable so as to modify a total quantity	Applies to productivity, wages, incomes, car ownership columns
	❶❷ Effects solved in equilibrium - different numbers identify separate (partial) equilibria	Each such symbol must appear at least twice, in green cells
Row/ column headings	Variable is exogenous (input for Base Case is exogenous, in Group 1)	Only shown where this is a fixed feature of the design. Many variables in most models can be made partly or wholly exogenous for "what if..." tests
	Variable is partly exogenous	
	Changes in this variable are modelled at two spatial levels	Row variables may influence column variables at either level or both
Heading border	Variable is constrained by planning policy inputs	Only shown where input is required; other policy inputs may be possible

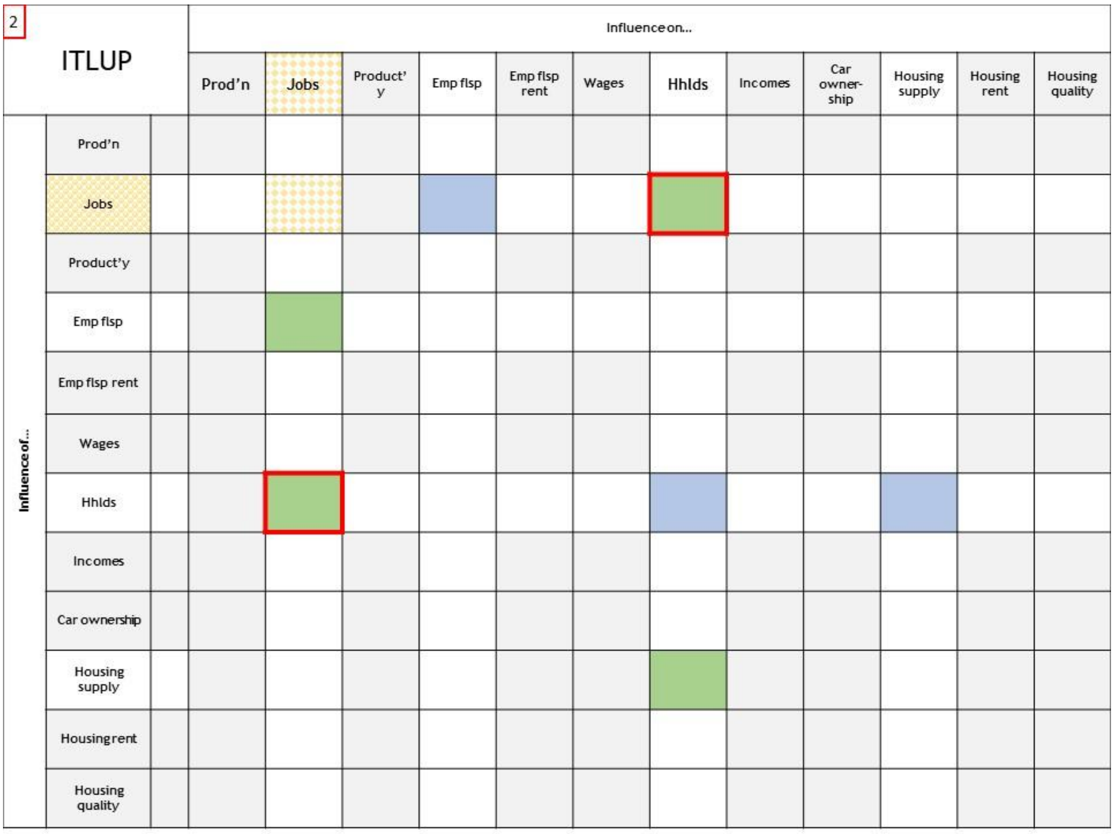
Figure 5-4 Dynamic City Model (DCM) (Group 1)



1

Dynamic City Model (DCM)		Influence on...											
Influence of...		Prod'n	Jobs	Product'y	Emp flsp	Emp flsp rent	Wages	Hhlds	Incomes	Car owner-ship	Housing supply	Housing rent	Housing quality
	Prod'n												
	Jobs							🟩					
	Product'y												
	Emp flsp												
	Emp flsp rent												
	Wages												
	Hhlds		🟩										
	Incomes												
	Car ownership												
	Housing supply												
	Housing rent												
	Housing quality												

Figure 5-5 ITLUP (Group 2)



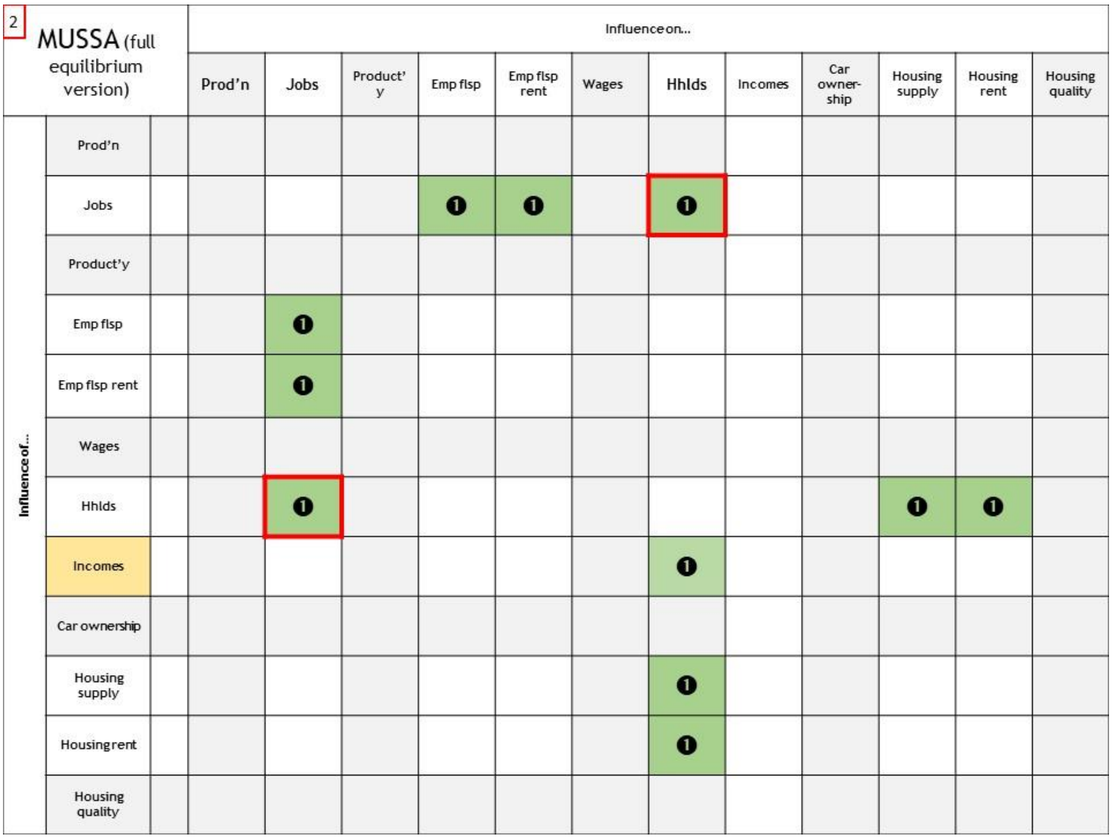
2

Influence on...

Influence of...

ITLUP	Prod'n	Jobs	Product'y	Emp flsp	Emp flsp rent	Wages	Hhlds	Incomes	Car ownership	Housing supply	Housing rent	Housing quality
Prod'n												
Jobs		🟨		🟦			🟩					
Product'y												
Emp flsp		🟩										
Emp flsp rent												
Wages												
Hhlds		🟩					🟦			🟦		
Incomes												
Car ownership												
Housing supply							🟩					
Housing rent												
Housing quality												

Figure 5-6 MUSSA/CubeLand (Group 2A)



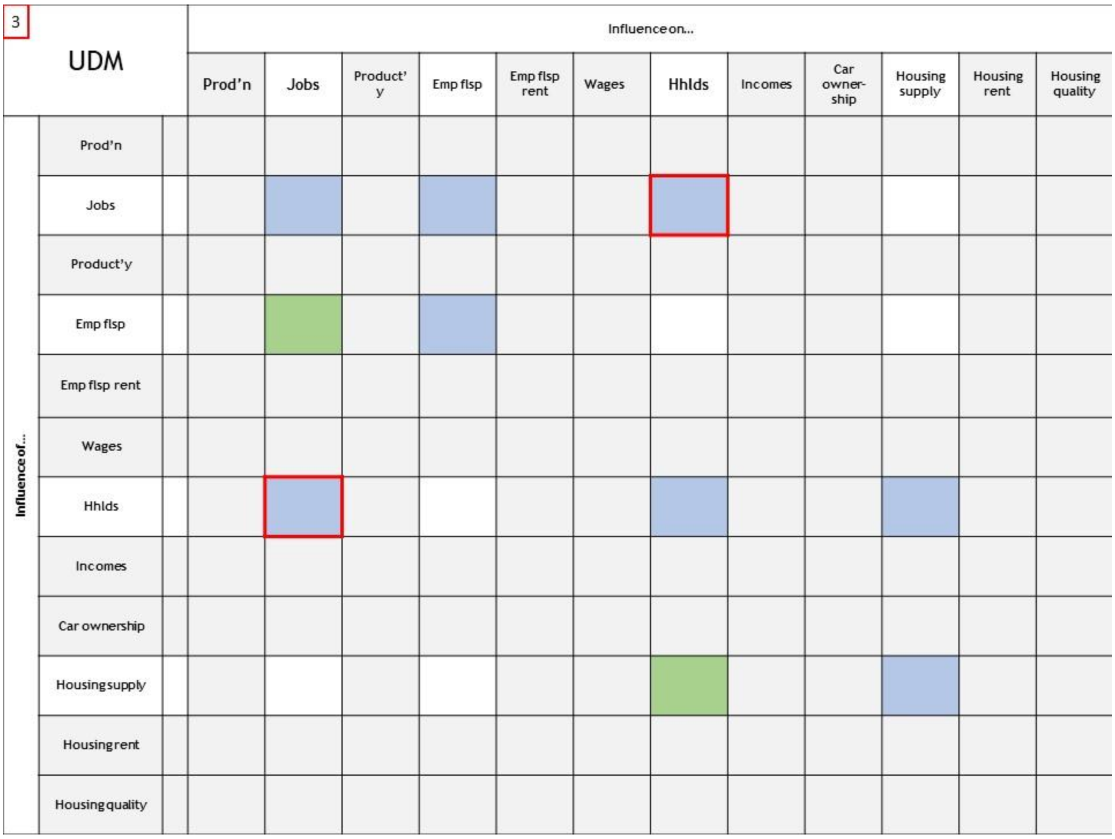
2

Influence on...

Influence of...

MUSSA (full equilibrium version)	Prod'n	Jobs	Product'y	Emp flsp	Emp flsp rent	Wages	Hhlds	Incomes	Car ownership	Housing supply	Housing rent	Housing quality
Prod'n												
Jobs				❶	❶		❶					
Product'y												
Emp flsp		❶										
Emp flsp rent		❶										
Wages												
Hhlds		❶								❶	❶	
Incomes							❶					
Car ownership												
Housing supply							❶					
Housing rent							❶					
Housing quality												

Figure 5-7 UDM (Group 3)



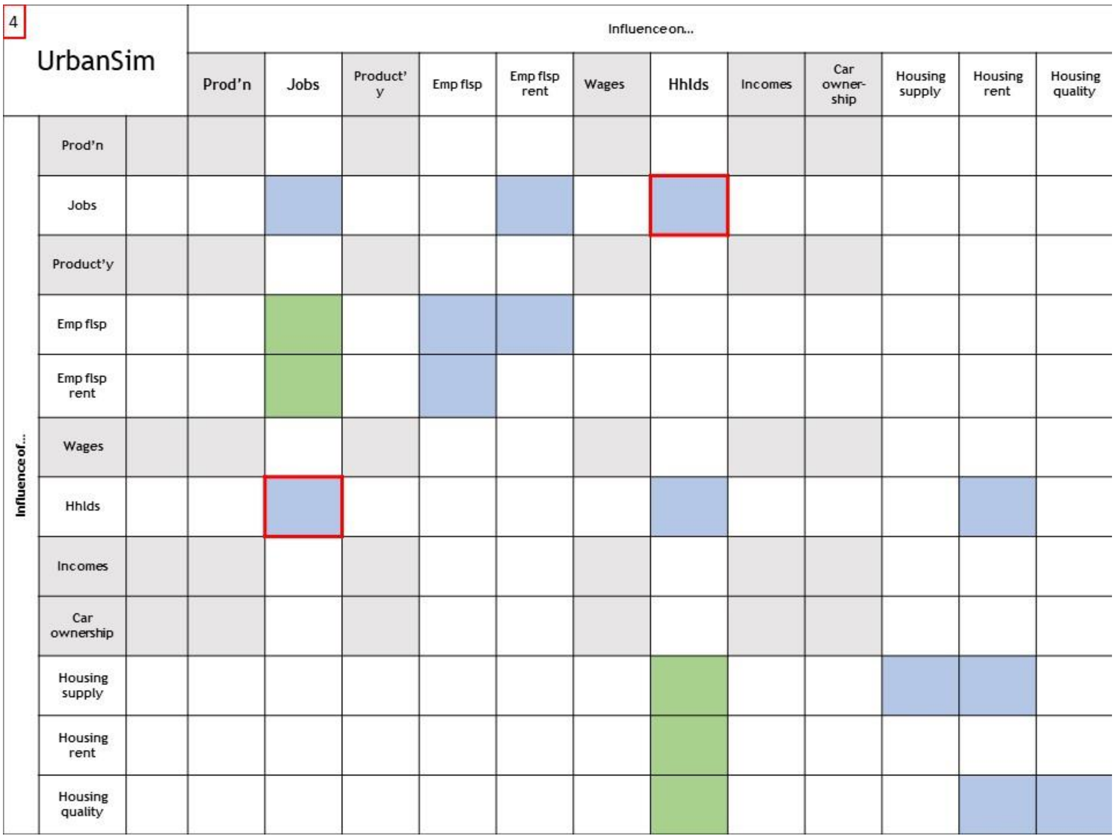
3

Influence on...

Influence of...

UDM	Prod'n	Jobs	Product'y	Emp flsp	Emp flsp rent	Wages	Hhlds	Incomes	Car owner-ship	Housing supply	Housing rent	Housing quality
Prod'n												
Jobs		🟦		🟦			🟦					
Product'y												
Emp flsp		🟩		🟦								
Emp flsp rent												
Wages												
Hhlds		🟦					🟦			🟦		
Incomes												
Car ownership												
Housing supply							🟩			🟦		
Housing rent												
Housing quality												

Figure 5-8 UrbanSim (Group 4)



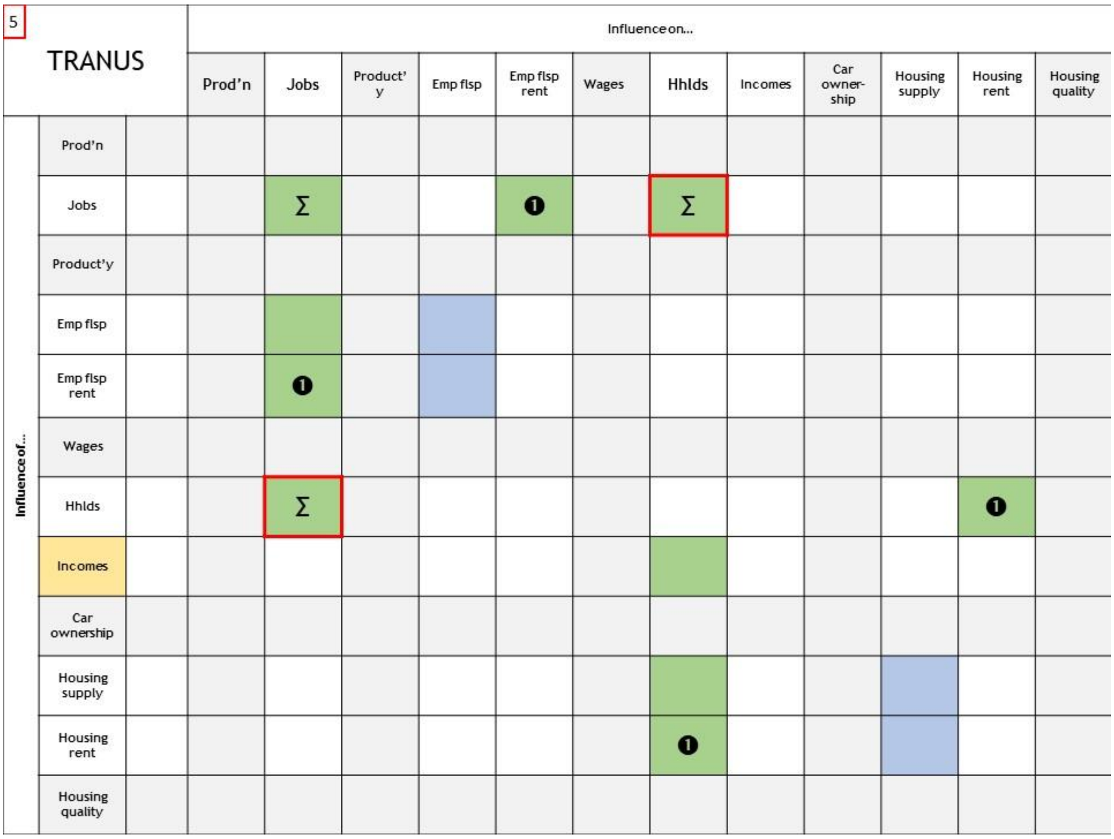
4

Influence on...

Influence of...

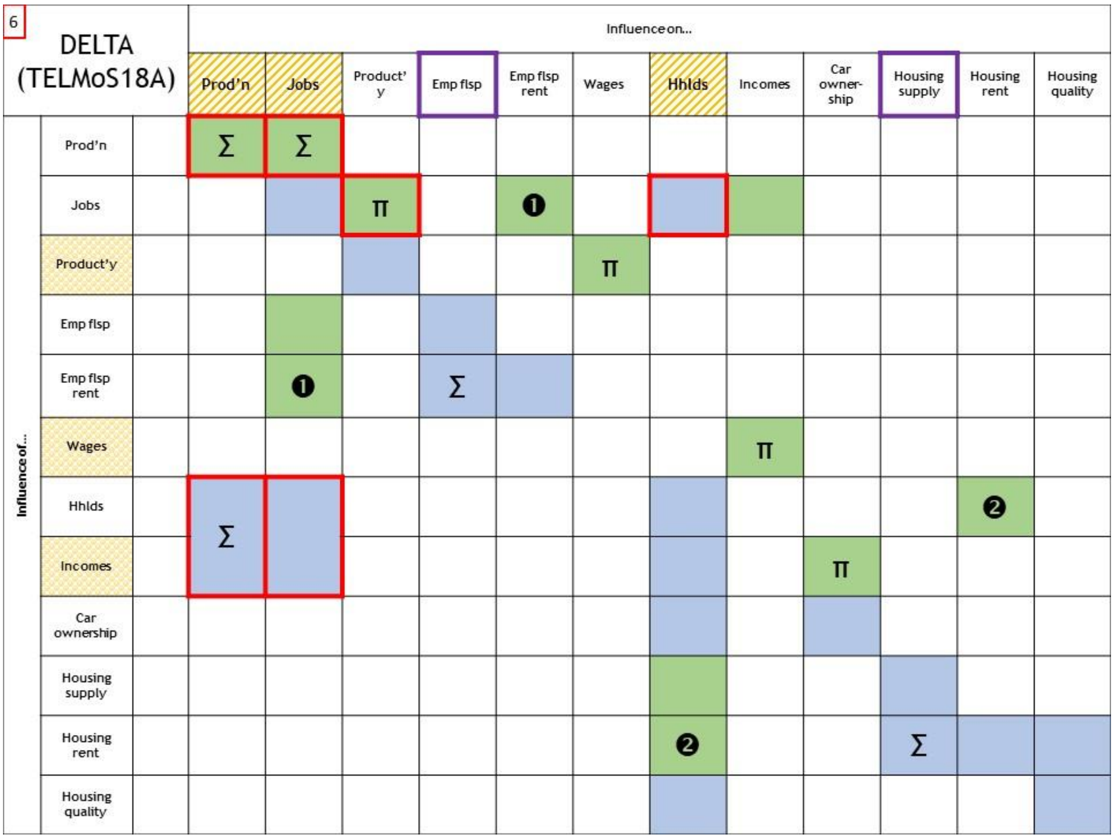
UrbanSim	Prod'n	Jobs	Product'y	Emp flsp	Emp flsp rent	Wages	Hhlds	Incomes	Car owner-ship	Housing supply	Housing rent	Housing quality
Prod'n												
Jobs		🟦			🟦		🟦					
Product'y												
Emp flsp		🟩		🟦	🟦							
Emp flsp rent		🟩		🟦								
Wages												
Hhlds		🟦					🟦				🟦	
Incomes												
Car ownership												
Housing supply							🟩			🟦	🟦	
Housing rent							🟩					
Housing quality							🟩				🟦	🟦

Figure 5-9 TRANUS (Group 5)



5 TRANUS	Influence on...											
Influence of...	Prod'n	Jobs	Product'y	Emp flsp	Emp flsp rent	Wages	Hhlds	Incomes	Car owner-ship	Housing supply	Housing rent	Housing quality
Prod'n												
Jobs		🟩 Σ			🟩 ❶		Σ					
Product'y												
Emp flsp		🟩		🟦								
Emp flsp rent		🟩 ❶		🟦								
Wages												
Hhlds		Σ									🟩 ❶	
Incomes							🟩					
Car ownership												
Housing supply							🟩			🟦		
Housing rent							🟩 ❶			🟦		
Housing quality												

Figure 5-10 DELTA (Group 6)



6 DELTA (TELMoS18A)	Influence on...											
Influence of...	Prod'n	Jobs	Product'y	Emp flsp	Emp flsp rent	Wages	Hhlds	Incomes	Car owner-ship	Housing supply	Housing rent	Housing quality
Prod'n	🟩 Σ	🟩 Σ										
Jobs		🟦	🟩 π		🟩 ❶		🟦	🟩				
Product'y			🟦			🟩 π						
Emp flsp		🟩		🟦								
Emp flsp rent		🟩 ❶		🟦 Σ	🟦							
Wages								🟩 π				
Hhlds	🟦 Σ	🟦					🟦				🟩 ❷	
Incomes							🟦		🟩 π			
Car ownership							🟦		🟦			
Housing supply							🟩			🟦		
Housing rent							🟩 ❷			🟦 Σ	🟦	🟦
Housing quality							🟦					🟦

Figure 5-11 TIGRIS (Group 6)

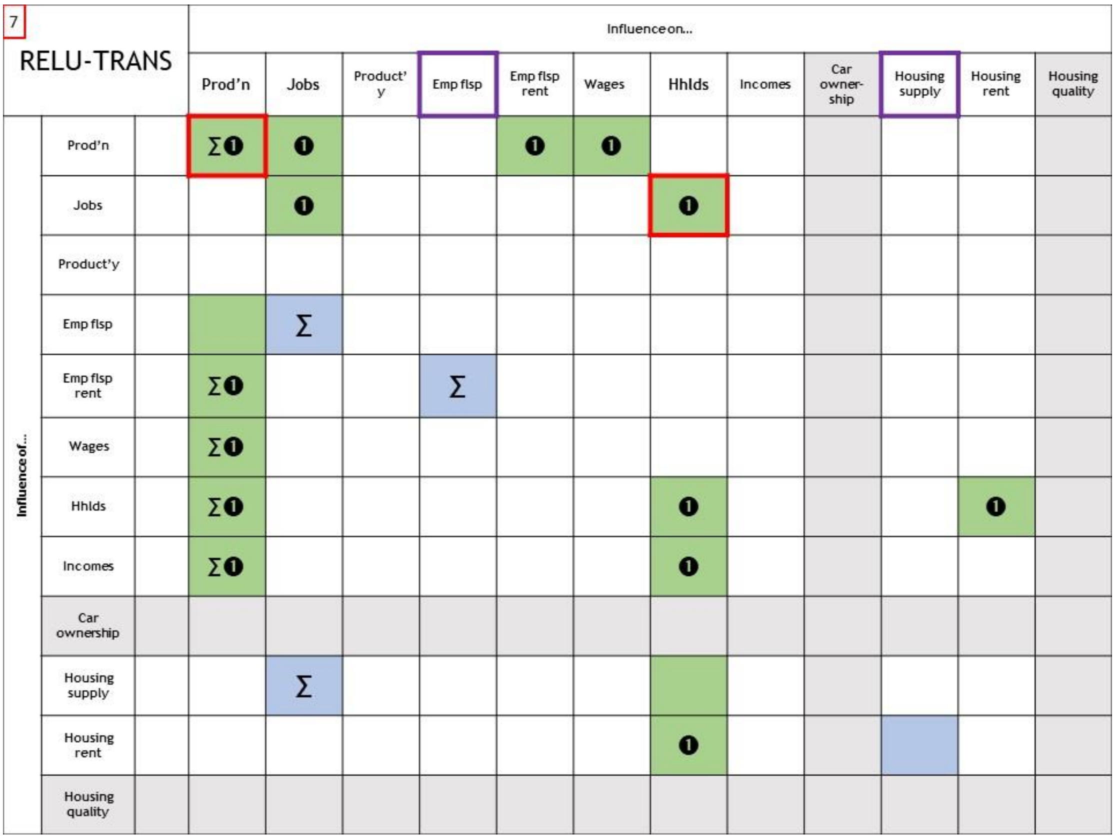
6

TIGRIS

Influence on…

Influence of…	Prod'n	Jobs	Product'y	Emp flsp	Emp flsp rent	Wages	Hhlds	Incomes	Car owner-ship	Housing supply	Housing rent	Housing quality
Prod'n												
Jobs		🟦		🟦	🟩		🟦					
Product'y												
Emp flsp		🟩		🟦								
Emp flsp rent		🟩		🟦								
Wages												
Hhlds		🟦									🟩	
Incomes												
Car ownership												
Housing supply							🟩			🟦		
Housing rent							🟩			🟦		
Housing quality							🟩					

Figure 5-12 RELU-TRAN (Group 7)



7

RELU-TRANS

Influence on…

Influence of…	Prod'n	Jobs	Product'y	Emp flsp	Emp flsp rent	Wages	Hhlds	Incomes	Car owner-ship	Housing supply	Housing rent	Housing quality
Prod'n	🟩 ∑❶	🟩 ❶			🟩 ❶	🟩 ❶						
Jobs		🟩 ❶					🟩 ❶					
Product'y												
Emp flsp	🟩	🟦 ∑										
Emp flsp rent	🟩 ∑❶			🟦 ∑								
Wages	🟩 ∑❶											
Hhlds	🟩 ∑❶						🟩 ❶				🟩 ❶	
Incomes	🟩 ∑❶						🟩 ❶					
Car ownership												
Housing supply		🟦 ∑					🟩					
Housing rent							🟩 ❶			🟦		
Housing quality												

5.12.11 These diagrams are hopefully helpful as illustrations of the differences between different models and groups of models. They show in particular how the scope and complexity of the models generally increases from Group 1 to Groups 6 and 7 in terms of the range of endogenous variables. It should however be remembered that there are other dimensions of sophistication, not apparent in these diagrams, in how variables and relationships are represented e.g. the potential for site-level detail in UrbanSim or the bid-rent function in MUSSA.

6 REQUIREMENTS FOR TRANSPORT APPRAISAL

6.1 Introduction

6.1.1 This chapter sets up a list of questions that relate to

- requirements for LUTI models to contribute to transport appraisal (e.g. producing appropriate outputs), and
- other issues affecting their possible use in transport appraisal, e.g. the assumptions and calibration affecting those outputs.

6.1.2 These questions reflect what was agreed about DfT's interests in this review. We are particularly interested in models which have been used by government (at whatever level) in the formal appraisal (i.e. *ex ante* evaluation) of transport proposals, or which have been shown to be applicable to such appraisals even if not used in practice. "Transport proposals" may include

- investments in transport infrastructure (or disinvestments, such as removing urban motorways);
- pricing (e.g. public transport (transit) tariffs, highway tolls, road pricing, parking charges/taxes, fuel taxes);
- regulation (e.g. speed limits, parking controls).

6.1.3 We are more particularly interested in models whose results are (or could be) used in cost-benefit analysis of such transport proposals, whether that use is

- as input to a conventional transport cost-benefit analysis (i.e. one where changes in consumer surplus are estimated from changes in the generalised costs of travel and the numbers of travellers)
- as the basis for an alternative cost-benefit analysis (e.g. one where changes in consumer surplus are estimated from changes in accessibility and in other variables affecting the utility of location, and from the numbers of households experiencing those changes).

6.1.4 Taking present TAG as representative of "conventional transport cost-benefit analysis", then the most common requirements for LUTI modelling are to forecast changes in employment location as the basis for

- dynamic agglomeration calculations;
- benefits arising from individuals moving to better/worse paid jobs;
- benefits from individuals being attracted into work by easier travel to work (i.e. allowing for change in location of the available work).

6.1.5 Further requirements may arise to calculate

- alternative land-use patterns for appraisal under base and modified land-use - in many cases this requirement would be met by the same outputs of changed population and employment, subject to the definitions of these outputs being such that they can be used to modify the transport model inputs
- land value uplift for significant land-use change – though this can also be done directly using (for example) the recent research by ITS Leeds[34].

6.1.6 The accessibility-based land-use/transport appraisal (AbLUTA) approach[35] is taken as an example of an alternative cost-benefit analysis. This requires forecasts of household and employment location and of floorspace development, with households and employment locating in the various floorspace markets, with rent adjusting to find short-term equilibria in each market. The outputs must support the calculation of a utility function for households, changes in costs and revenues for producers and property owners/developers, and changes in revenues and expenditures for the public sector[36].

6.1.7 Whilst the focus is on ex ante appraisal, some of the points made about calibration (7.15), validation (7.16) and controlling to detailed scenarios (7.7) are also very relevant to ex post evaluation.

6.2 Specific questions to consider

6.2.1 The following table sets out a list of questions to consider in assessing the ability of different types of models to contribute to transport appraisal. The questions broadly run from scope, through "content" (variables represented) to questions of appraisal. The answers are developed and discussed in the following chapter.

Table 6-1 Questions relevant to appraisal

Question	see
Can the model be applied at an appropriate spatial scale and scope? i.e. appropriate to the intervention, the responses and the appraisal? (e.g. a model in which the zones are regions isn't appropriate to modelling active modes)	7.2
How does the model treat time? e.g. does it represent a wholly static equilibrium, a series of five-year steps, an annual series, etc?	7.3

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[34] Nellthorp, J, M Ojeda Cabral, D Johnson, C Leahy, L Jiang (2019): *Land Value and Transport (Phase 2): Modelling and Appraisal*. Final Report to TfN, WYCA and EPSRC. Institute for Transport Studies, University of Leeds. Note that this can certainly be used to calculate changes in land value resulting from transport improvements. It can also be used to calculate changes in the value of residential land resulting from changes in the distribution of employment (e.g. jobs relocated to more easily accessible locations), but there is a question whether that is theoretically valid given the way the hedonic price models were estimated. (There is also a question of whether the commercial land value models were ever completed.)

[35] Simmonds, D (2023): *Accessibility-based land-use/transport cost:benefit analysis for place-based appraisal.* Paper prepared for European Transport Conference, Milan. Available at https://aetransport.org/

[36] It is emphasised that taxes and public expenditures are treated as transfers in this; any gain to the public sector is at the expense of another agent. The analysis of impacts on the public sector is part of the distributional analysis, not an additional source of benefit.

Question	see
How does the land-use model link to transport modelling e.g. is it [a] designed to be fully integrated with a particular transport model, and only operable as such? (At one time that was for example the case with MEPLAN.) [b] designed to connect with any conventional transport model, i.e.it does not need its own specific transport model, though it may have one.	7.4
Can the model take account of all the relevant aspects of the transport intervention to be tested? (including non-transport effects that will impact on land-use, such as land take and subsequent noise/pollution)	7.5
Can the model take account of relevant accompanying measures, e.g. changes in planning policy? Can it be used to test other alternative interventions? (e.g. locating future development closer to existing rail stations rather than building new stations or new lines). In each case, is it clear what accompanying measures are implicit?	0
Does the model output [a] microdata for use in an activity- or agent-based model? [b] disaggregate land-use data? [c] aggregate data sufficient for input to a four-stage transport model? [d] less than that?	7.7
Does the disaggregation of economic/employment sectors in the model sufficiently separate sectors operating on different spatial scales and affecting by different types of transport?	7.9
Does the disaggregation/definition of households allow for the complexities of households (e.g. multi-worker households, perhaps with different occupations), for income from wages and other sources, and does it provide a basis for distributional weighting of appraisal results? How does it treat car ownership?	7.10
Does the disaggregation of workers sufficiently separate different kinds of labour markets (e.g. by occupation, skill or income level)? Does it allow for interactions between these e.g. people working in jobs for which they are over-qualified because more appropriate jobs are not accessible to them?	7.11
Does the modelling of labour markets allow for variable levels of [a] unemployment and/or [b] unfilled vacancies ?	7.12
Are supply-side choices represented as well as demand-side? E.g. [a] does housing supply respond to changing demand (if allowed to do by planning policy) [b] do businesses exercise any choices, or are they all assumed to passively go where consumers (intermediate or final) choose to purchase the goods and services they supply? [c] do households have any choice over whether or how much to work if real wages (i.e. net pay minus generalised cost of commuting) improve or deteriorate?	7.13
How strong is/could be the calibration approach?	7.15
How much (if any) validation evidence is there to support the model? How much does this matter?	7.16
Which of the models are [a] fully consistent, [b] partially consistent, or [c] fundamentally inconsistent with the theory behind the appraisal approach? This will have different answers depending on the appraisal approach considered	7.17
How consistent are the models with the principles of New Economic Geography?	7.18

Question	see
Which of the models output [a] a full set of appraisal results? (directly from the model)? [b] data which can be used (e.g. in WITA) to calculate appraisal results? [c] less than that? [exclude these].	7.19
Which of the models have actually been used in appraisal or in business cases, and if so, where and how?	7.20

7 ABILITY OF MODEL TYPES TO MEET THOSE REQUIREMENTS

7.1 Introduction

7.1.1 This chapter considers the models or groups of models against each of the questions raised in the previous chapter. This is an intermediate stage in getting to the overall assessment of the models' potential contributions to appraisal, addressed in the following chapter.

7.2 Spatial scale and scope

7.2.1 At national level, the modelling needs to focus on economic interactions between larger spatial units and to recognize the constraints and inertia that limit relocation of the population between such units, especially over longer distances. At a local level, to consider impacts (and the interactions with development) below local authority level, the modelling needs to focus on the characteristics of the available built stocks, including the local environments in which housing, offices etc are located. SCGE- and spatial input-output based models are clearly strongest at the national economic level. All of the models considered except the SCGE-based ones can function at a local level, but those which can function at parcel or zone level (i.e. UrbanSim, plus to some extent PECAS) have the most capability in this respect.

7.2.2 Displacement effects – and the distribution of displacement - are critical to the appraisal of interventions that are intended to promote growth in particular locations or types of locations. This is more easily dealt with by a model which explicitly covers the whole of the economy which is of interest and may be affected[37]. For Department for Transport purposes, the economy is that of the UK, but for practical purposes it may be reasonable to assume that the effects of interventions in England will not extend to Northern Ireland, and hence that consideration of displacement effects across Great Britain would be sufficient.

7.2.3 Whilst there are advantages to modelling the whole of Great Britain in testing anything that might have regional displacement effects, this does not necessarily mean that the whole of Great Britain has to be modelled in equal detail. Apart from questions of spatial aggregation (considered further below), more complex model packages often allow a distinction between full modelling in the core area of interest and more limited modelling across the rest of the economy. The more limited modelling can sometimes reduce data requirements and model run times,

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[37] The question of whether or when a model covering the whole economy can forecast net changes in employment as a result of transport or planning interventions is picked up in section 7.12.

and can sometimes avoid delicate issues of "modelling other authorities' policies", but it is important to understand and agree what is implied by the limitations. In the DELTA package, for example the standard treatment of "buffer zones" (if used) ignores floorspace and the markets for space, and ignores congestion: it therefore implicitly assumes that space and transport capacity will adapt to any changes in demand that occur in those areas[38]. This may or may not be appropriate in any particular case.

7.2.4 A key question of theory is whether a national model with local capabilities needs to have a multi-level spatial structure with different variables affecting different levels (as in TIGRIS and DELTA) or whether the differences between "inter-regional" and "intra-regional" effects can be properly represented without such a structure. The argument for a "multi-level and multi-scale" approach have been set out in Spiekermann and Wegener[39].

7.2.5 The implications of zone sizes for results is an under-researched area, not least because of the work involved in setting up model systems at multiple levels. One study, using UrbanSim applied to Brussels[40], concluded that "the influence of the scale [of zones] on policy evaluation based on Land Use and Transport Interactions models appears limited when it is only intended to compare scenarios, but it will have a crucial role when evaluations are based on absolute variations or threshold values". Another study[41] concluded that "the choice of zoning is fundamentally important".

7.2.6 A potential alternative is the idea of "adaptive zoning" whereby fine zones are aggregated to larger units within the workings of the model, so that each zone interacts with small zones close by and increasingly aggregated zones at further distances[42].

7.2.7 Previous criticism of city region models has pointed out the deficiencies of closed-system models that are unable to deal with displacement into or out of the modelled region; these are all the more significant when the potential for investments in one region to affect "levelling up" in other regions is considered. So it is probably reasonable to say that any future model should be "national with more detail where needed" (whatever "national" may mean) rather than purely

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[38] See for example Dobson, A C, E C Richmond, D C Simmonds, I Palmer and N Benbow (2009): *Design and use of the new Greater Manchester Land-Use/Transport Interaction Model (GMSPM2).* Paper presented to the European Transport Conference, 2009. Available at https://aetransport.org/.

[39] Spiekermann K and Wegener M (2018): Multi-level urban models: Integration across space, time and policies. *Journal of Transport and Land Use* vol 11 pp 67-81.

[40] Jones, J, D Peeters, I Thomas (2016): Scale effect in a LUTI model of Brussels: challenges for policy evaluation. *European Journal of Transport and Infrastructure Research*, vol 17(1).

[41] Cabrera Delgado, J and P Bonnel (2016): Level of aggregation of zoning and temporal transferability of the gravity distribution model: The case of Lyon. *Journal of Transport Geography*, vol 51 pp 17-26

[42] This idea was developed by Alex Hagen-Zanker in his PhD dissertation: see for example Hagen-Zanker, A and Y Jin (2011): *Adaptive zoning and its effectiveness in spatial economic activity simulation*, available at https://www.researchgate.net/profile/Alex-Hagen-Zanker/research. It is not clear whether the approach has ever been used in practice.

regional. (This was recognized in work on LonLUTI and FLUTE, both of which were eventually extended to cover the whole of Britain[43].) This also extends into the "what happens elsewhere?" e.g. what the analysis of potential interventions in one city region should assume about interventions in adjoining city regions.

7.2.8 Microsimulation offers the possibility of modelling without zones. This can be achieved in parcel-based applications of UrbanSim, but this usually depends on inputs from a zonal transport model. Fully "azonal" modelling has been illustrated in some academic projects[44].

7.3 Treatment of time

7.3.1 The degree to which it is necessary, first for modelling purposes and then for appraisal purposes, to model land-use change as an explicit process of change over time is one of the most important bases for choosing one modelling approach rather than another.

7.3.2 In some respects, the prevalence of static or largely-static models, from the 1964 Lowry model to the present RELU-TRAN and PECAS models, is somewhat curious, given that it is universally agreed that land-uses are generally slow to change and that their response to a shock, such as a significant change in accessibility thanks to a transport improvement, can take years or decades to work out in full. This prevalence can perhaps be attributed to either or both of

- the predominance of equilibrium as a central concept in economic theory, and especially in urban microeconomics, and
- the practicality of mainly-static modelling, especially in terms of more limited data collection and (relative) ease of calibration.

7.3.3 Users' perceptions of the "reasonableness" of the model, or otherwise, should play a part in assessing the relative merits of different approaches. The definition of "users" needs to include the "hands-on" professional staff operating the model, other professionals who need to consider the results of the modelling and appraisal, and the public and the political decision-makers who are the "end users" of such analysis. It is probably safe to say that many users find a model which works in relatively short time steps and forecasts impacts as emerging gradually more intuitively convincing than one in which the whole city region adapts in one step to the change being appraised[45]. It also helps that in short-step dynamic modelling it

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[43] The criticisms of the earlier version of LonLUTI were set out in Wenban-Smith, A, and T van Vuren (2009): *Using transport models in spatial planning: issues from a review of the London land-use/transport interaction (LUTI) model*. Paper presented to European Transport Conference. The present version (see reference in footnote 70, p74) covers the whole of GB.

[44] See for example N Kuehnel, D Ziemke, R Moeckel, K Nagel (2020): The end of travel time matrices: individual travel times in integrated land use/transport models. *Journal of Transport Geography* vol 88.

[45] For example, a small-scale study (circa 1996) of planners exposed to results from a variety of forecasting methods (from professional judgement to LUTI modelling) found that whilst there was resistance to complexity, it "was perceived as beneficial if it made explicit the processes that underlay the model results… the production of intermediate indicators such as rents and accessibilities was seen to aid transparency"

is usually possible to show a plausible sequence of different changes emerging in turn and then interacting e.g. rents change first (because some choices change); these affect other activities; then over time floorspace supply changes in response to the rent changes.

7.3.4 There is a recurrent question about "path dependency" – whether the order in which different changes occur (e.g. a major road improvement and a new railway in the same corridor) has any impact. The question is often phrased assuming that there is some end state equilibrium to which the system is tending, but it is valid in even in the context of a continuously changing system: do the land-use outcomes which may affect the appraisal of the interventions vary according to the order in which they are introduced?. The suggested answer is that it depends on the degree to which there are irreversible, or only very slowly, irreversible processes of change in the model. If everything in the model is entirely reversible – for example, because the model assumes that building stocks are perfectly and instantaneously elastic with respect to demand – then the sequence of changes will have little or no effect, and there will be no path dependency.

7.3.5 An example might be that if the major road improvement is built first, land allocated for employment uses might be taken up for distribution and logistics centres; but that if the railway was built first, it might attract significant office development, with much higher total employment. This raises the question of whether agents in the model are myopic (knowing only about the present, or about the past) or have partial or perfect foresight. In the road-first case, if developers had sufficient foresight and sufficient confidence in the expectedrailway investment, they would know that the railway was following and that (typically) office development would be the more profitable; the "obvious" option of building warehouses would be ignored or taken up only on a smaller scale.

7.3.6 In the majority of the models reviewed, agents are myopic, having only information about the past or about parts of the present situation. One of the RELU-TRAN papers describing the model as embodying perfect foresight, but it is not entirely clear how that is achieved; if strictly true it would presumably apply to LUISA as well, given the near-identical designs (see Appendix H).

7.3.7 At the simpler end of the modelling range, the static adjustment models have in themselves no concept of time, but require input data which will normally represent forecasts for some future date. They could be run using Base and Alternative transport outputs for year *t*, but Base land-use inputs for (say) year *t*+20. In that process the Alternative land-use outputs would also be for year *t*+20 and the results could be considered as representing an "equilibrium" outcome after the (perfectly elastic) responses had worked out.

7.3.8 At the other extreme of modelling complexity, the urban SCGE models appear in practice to be run mostly as static equilibrium models, but have the option to be run with floorspace changes occurring over time, which leaves them, in terms of dynamics, very similar to the Martin Centre models (Group 5: MEPLAN,

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(Still, B G (1997): *Transport impacts on land use: potential methods and their relevance to strategic planning.* Summary of PhD dissertation.). See also Lapparent reference in Box 8:1.

TRANUS and PECAS), which are likewise mostly equilibrium models. These models are usually run in five-year steps. i.e. with the equilibrium components of the land-use model and the separate equilibrium transport model being run at every fifth year, with the development model (and any other incremental components) being calculated for the five year steps. (As noted in chapter 2, LUTI models are **not** normally run to find an equilibrium **between** land-use and transport; the main exceptions are the urban SCGE models (Group 7), if run in their full-equilibrium form.)

7.3.9 The five-year step is usual, but largely conventional rather than justified by any particular evidence. The one study of this question that the present author has found used the TRANUS package, applied to the city of Sapporo (Japan). It concluded that with that particular model the best interval would be 3.3 years, but that the conventional five-year step was acceptable (see Box below).

Box 7:1 Determination of a desirable time step – Sapporo TRANUS model

Vichiensan, V, K Miyamoto, K Katazume (2003): Determination of a desirable time step for quasi-dynamic urban model with Sapporo test bed. *International Journal of Urban Sciences*, vol 7, pp 102-117.

The study considered the alternatives of dividing a 10-year validation forecast into one 10-year step, two five-year steps (with the (mostly equilibrium) land-use model and then the transport model run at the mid-point), three 3.3-year steps, four 2.5 year steps, or five two-year steps. The results were considered in terms of measures of accuracy and uncertainty; accuracy increased with shorter steps (especially with two steps rather than one), but so did uncertainty. The best trade-off between accuracy and uncertainty was judged to be obtained with three 3.3-year steps, with two five-year steps being judged acceptable. The present author is not wholly convinced by the trade-off or by the reasons given for uncertainty increasing with shorter time-steps; the strongest conclusion is that the accuracy of the 10-year forecast improves with at least one intermediate year, probably because this updates the transport costs. If that explanation is correct, it would probably apply to LUTI models in general.

7.3.10 A German study using a microsimulation land-use model that runs in one-year steps tested the consequences of running the transport model at 15, 5 or 2-year intervals. Like the Sapporo TRANUS-based study mentioned above, it too found in favour of five-year intervals, though the conclusions may reflect specific characteristics of the particular model used (see Box below).

Box 7:2 Determination of a desirable time step – Munich FABILUT model

Llorca, C, N Kuehnel, R Moeckel (2020): Agent-based integrated land use/transport models: a study on scale factors and transport model simulation intervals. *Procedia Computer Science* vol 170 pp733–738.

This study used the FABILUT (Flexible, Agent-Based Integrated Land-Use/Transport) modeling suite (see alsoAppendix G, section **Error! Reference source not found.**). FABILUT consists of the land use model SILO (Simple Integrated Land use Orchestrator) and a microsimulation (agent-based) transport model implemented in MATSim. SILO uses a synthetic population consisting of households, persons, dwellings and jobs from one simulation year to the next, SILO models demographic changes (such as marriage, birth and death), real estate developments (such as construction, renovation, housing demolition) and household relocation. Each household of the synthetic population is microscopically simulated. Commute travel times and accessibilities of locations are important in the household relocation process; both are updated by MATSim that is executed in selected years. In such transport model years, the current state of the synthetic population in SILO is converted into MATSim agents which are used to simulate traffic flows in MATSim.

The study found, not surprisingly, that the changes in average travel times were greater when the transport model was run less frequently; the difference in model results between running the transport model in alternate years and every fifth year were small. They found a problem with the shorter, 2-year interval, in that the results were unstable with commute times oscillating between successive years. The latter problem would appear (to the present author) to be due to stochastic variation in the outputs of the microsimulation transport model (the implication being that the shorter interval would not be a problem if the stochastic variation could be eliminated (for example – but not only – by running a conventional transport model to equilibrium).

7.3.11 The present author's experience (mainly with DELTA) has included running the transport model at 10- 5- and 2- year intervals, with the land-use model running in one-steps in all cases. A two-year interval tends to give more stable results overall, partly because the changes in transport costs between successive transport model runs are smaller, and partly because there are fewer years of land-use change before the transport feedback effects are felt. This is admittedly based on the experience of different implementations of very similar models with different transport model frequencies, and not on a systematic comparison of different steps in an otherwise identical model. The two-year frequencies were made possible by relatively coarse zone systems (compared with "standard" transport models) and fast, "strategic" treatments of transport with very little detail of networks[46].

7.3.12 For any model that works in time steps, it is desirable – to keep transport costs consistent with forecast land-uses – that the transport model should be run as often as the land-use model is run. However, there are more questions around land-use models which are designed to work in short time steps, typically producing results

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[46] Mainly MVA Consultancy's START package, TRL'S STM, and DSC's HSTM. See respectively Bates J., Brewer M., Hanson P., McDonald D. & Simmonds D.C. (1991). Building a strategic model for Edinburgh. *Proceedings of the PTRC Summer Annual Meeting, Seminar G*, Brighton, pp 165-181; Aramu, A, A Ash, J Dunlop and D Simmonds (2006): SITLUM - the Strathclyde Integrated Transport/Land-Use Model. *Proceedings of the EWGT2006 Joint Conferences*, Politecnico di Bari; and Simmonds, D C (2019): Integrated modeling in the UK: practical usability of integrated models. *Journal of Transport and Land Use*, vol 12, pp 327-334. The last of these includes some further discussion of the contexts in which it is necessary to do many rapid runs of a LUTI model and hence where a fast if limited modelling of transport is required.

for each year (Groups 3, 4 and 6). These land-use models are run recursively, with the outputs from each one step providing inputs to the next step; there is therefore very little additional cost in setting them up for one-year rather than two-year or longer steps (and some savings, from greater simplicity); it may also be a necessity to run them in one-year steps in order to get reasonable linkages between different processes[47]. However, conventional transport models are typically more expensive to set up for different years and, in particular, time-consuming to run. There is therefore an issue of how often the associated transport models should be run, if it is impractical or unaffordable to run them for every modelled year. Here too, every fifth year is often taken as a reasonable compromise, though irregular intervals may be used for particular reasons[48], and on some occasions the transport modelling outputs have to be taken for the forecast years already available from previous work. What is clear, however, is that where the transport model can only be run at less frequent intervals, the land-use modelling step should **not** be increased to match, since to do so will undermine the dynamic logic of the land-use model.

7.3.13 All of this discussion (except for the FABILUT model) assumes a "static" transport model where the demand for transport is determined by land-uses (or related variables such as external-to-external traffic across a region) at that point in time, and the supply of transport is either fixed (infrastructure) or at most variable with respect to demand at that point in time (e.g. bus services). The discussion would become more complex if the transport model itself included dynamic responses.

7.3.14 Another related issue is whether the transport model responses should be different – in nature or just in sensitivity - when the transport model is being run at regular intervals in a LUTI context, compared to when it is run in stand-alone mode for a single, distant horizon year. This is discussed further in section 7.5.

7.4 Linkage/integration to transport models

7.4.1 One of the questions in the brief concerns which models need to work with particular transport models, and which can work with any standard transport model. Table 7-1 below summarises which of the models are

[a] **specifically integrated**: designed to be with a particular transport model i.e. having unique or unusual features which mean the land-use model only works with its own transport model and/or vice versa;

[b] **flexible**: designed to be fully integrated between transport and land-use, but operable as a connected model (i.e. another transport model could be substituted in provided this model works with standard "land-use" inputs and produces standard "transport" (generalised cost) outputs);

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[47] See discussion in Simmonds D, Wegener M, Waddell P (2013): Beyond equilibrium: advances in urban modelling. *Environment and Planning B*, volume 40, pages 1051 – 1070.

[48] e.g. TELMoS18A is set up to forecast to 2050, with transport model (TMfS) years in the base year (2018) and at 2019, 2025 and then every fifth year to 2045. The gap between 2019 and 2025 was allowed to avoid the complications of modelling the pandemic years and their immediate aftermath.

[c] **connected**: designed to work with a range of transport models i.e. the land-use model does not need its own transport model, though it may have one. (That transport model may be a very general-purpose package, as in the case of CubeLand, or one intended to meet much more specific requirements (e.g. in NELUM).

Table 7-1 Linkage/integration with transport models

Source: own assessment based on references listed in Appendices.

Group	Model/package	Linkage/integration	Notes
1	DCM	Connected	
2	QUANT		Base data from various sources; change from Base to Alternative input by user
3	MARS	?	
3	UDM	Connected (own transport model available but not required)	
4	UrbanSim	Connected	UrbanSim and other microsimulation models have the potential to provide microdata directly to activity-based/agent-based microsimulation transport models (other models produce aggregate outputs for use in a population synthesiser (see 7.8))
5	MEPLAN	Originally specifically integrated, later work was connected	These packages have in common the hypotheses that major transport demands are derived directly from the interactions modelled in the land-use model;
5	TRANUS	Specifically integrated, may have been used in connected form	
5	PECAS	Specifically integrated, may have been used in connected form	
6	DELTA	Connected (own transport model available but not required)	DELTA has mostly been used connected to a variety of conventional or strategic transport models, in LUTI mode where resources allowed and in LUMIT mode on other occasions.
6	TIGRIS	Probably flexible	TIGRIS was designed to work with the Dutch National Model System, but from published descriptions could work with other transport models.
7	LUISA	Integrated (own transport model) or connected (other transport models)	Has its own transport model, but can be run with inputs from other transport models
7	RELU-TRAN	Specifically integrated	RELU-TRAN is designed to forecast a general equilibrium where transport is in equilibrium with land-use and the economy, and vice versa. That said, the RELU component takes TRANS outputs as given and could be used separately.

7.5 Aspects of transport (and space)

Requirements for LUTI modelling – (components of) generalised costs

7.5.1 To be in scope for this review, the definition of LUTI models (in section 2.1) is one which "will respond to specific changes in transport networks and services". A minimum requirement in all cases is a set of matrices of generalised costs either by mode or appropriately averaged over modes. For full functionality, some of the models (e.g. RELU-TRAN) require separate time and cost components. For full integration with SCGE modelling, the transport model would need not only to separate out cost components but also to subdivide costs by the sector being paid (e.g. whether the costs go to fuel suppliers, railway operators, airlines etc) and potentially to disaggregate (or weight) time into "productive" and "unproductive" parts[49].

7.5.2 The range of passenger modes that needs to be considered depends on the spatial scale of the model system. Except perhaps for models where all the zones are large, it is essential to include walking as this provides the most important or only mode for very short distance interactions within dense centres. For models covering the whole of Great Britain or larger regions, air travel is also an essential contribution to accessibility at least for some business purposes.

7.5.3 Many of the models considered represent only the interactions between residents as labour and their workplaces, and between residents as consumers and the services they use, and therefore ignore freight transport and its impacts. There was (and possibly still is) a slightly separate tradition of using spatial input-output models such as those in MEPLAN and TRANUS for multi-regional economic models focussed much more on freight flows; those would not necessarily qualify as LUTI models in the sense used here. LUTI models reviewed which do explicitly take account of freight costs (and business travel costs) as an influence (possibly a very weak one) in industry location include PECAS and DELTA.

7.5.4 It is worth noting that whilst many of the models considered could work with all-mode passenger generalised costs which could be output (by purpose) from the accompanying transport models, there are a number of reasons why the land-use model may require input of generalised costs (or generalised cost components) by mode. These include

- representing a greater range of modes than any one transport model[50];
- applying a different choice hierarchy in accessibility calculations from that applied in the transport model;

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[49] This rather daunting specification is taken from the work on potential LUTI-SCGE integration described in H.4.5.

[50] For example, the DELTA model of France took car, public transport and active mode data from one transport model for travel within the Ile de France , and for car, air and rail for travel to, from and within the rest of France. See Bosredon, M and D Simmonds (2019): L'impact du Grand Paris Express sur le territoire national, in Prager (ed) op cit.

- calculating "absolute" accessibility when the transport model is incremental and can itself only calculate changes in accessibility[51].

7.5.5 An issue which was regularly discussed among LUTI practitioners some 20-25 years ago but seems to have been neglected since is the question of whether the coefficients - and possibly the choices of functional form - resulting conventional transport model calibration choice are appropriate in a LUTI context. The main issue is whether there is any degree of double-counting, e.g. if travel-to-work patterns are modified as a result of transport supply changes in both the transport and land-use model. In some cases it may be clearly appropriate to turn off the transport model response; for example, in the Martin Centre model (Group 5) travel-to-work patterns are only modified in the land-use model (as part of the household location process). In other cases, the issue may be more difficult: for example, in the same models the pattern of sales from service industries to households is forecast in the land-use model, but allow that pattern to change **only** in the land-use model means that shopping trips take (typically) five-years to respond to any change in transport supply, which seems implausibly slow.

Requirements for LUTI modelling – other variables

7.5.6 Some models (e.g. DELTA) also use distance between zones as a deterrent influence on household movement; others (e.g. TIGRIS) use generalised costs for this purpose as well.

7.5.7 Some of the models (including UrbanSim and DELTA) can take account of local environmental variables, including transport externalities which may be output from the transport model. These influence households' locational preferences through their utility functions. In the DELTA case, the initial design envisaged separate variables for noise and various different pollutants; in the event, the difficulties in averaging those (especially noise) to zonal level led to the adoption of "traffic density" (daily pcu-km per hectare) as a proxy. This had the merit of also being a proxy for accident risk, severance etc; it has the disadvantage that it should probably be adjusted to allow for some future improvements as the proportion of electric cars increases over time. In the case of parcel- or grid-based models, fine-scale calculation could for example take account of the differential effects of increased traffic on parcels beside or further away from highways.

Limitations on transport modelling in a LUTI context

7.5.8 Provided that the above requirements are met, the LUTI context does not impose many limitations on how exactly the transport modelling is done. It is true that land-use models have "traditionally" been implemented with fewer, larger zones than is "traditional" in transport modelling. However, that is decreasingly true –

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[51] In principle it might be possible for the dynamic models in Group 6 (or the static-adjustment ones in Group 1) to work entirely with changes in accessibility that could be calculated by an incremental transport model, if that included all the relevant modes in the appropriate hierarchy. But painful experience has taught that it is important to be able to examine the reasonableness of the "absolute" accessibilities.

LUTI model zone systems have become more detailed[52] - and at the same time, it is increasingly common to implement interfaces which convert land-use model output data to transport model zones and vice versa. Such interfacing means that the transport modelling can still be done at whatever level of detail is preferred; the remaining limitation is that the land-use model does not fully reflect the level of spatial detail at which the transport model is working unless the interfacing is sufficiently sophisticated (in effect, a lower-level model) to take account of the detail and to ensure that it is correctly represented in the more aggregate parts of the land-use model.

7.5.9 The way in which land-use models depend on the generalised cost outputs of the transport model does impose some restrictions, or at least raise questions, as to how the transport model is used to represent transport scenarios that are not standard supply changes. This was illustrated over a decade ago in modelling the potential impact of Local Sustainable Transport Fund (LSTF) measures on two different areas, using two similar LUTI models with similar transport models run by teams in different firms. The task in each case was to test the impact of an *x*% reduction in car traffic. One transport team implemented this by factoring down the car matrices before running the transport model; the other by gradually increasing the costs of driving until car traffic was reduced by *x*%. In the former case, the key effect in the land-use model was a modest improvement in accessibilities (from less congestion) leading to decentralisation of the most car-oriented households and employment; in the latter case, accessibilities worsened (from the cost increases, which had to outweigh any decongestion effects to achieve the *x*% reduction) giving opposite and more marked land-use effects. Whichever was correct, or more correct, the results illustrated the potentially dramatic LUTI effects of implementing a transport scenario in different ways.

7.5.10 There is a different practical issue around transport model run time. LUTI models have been successfully run with transport models taking up to a week (per single-year forecast), but obviously this greatly limits the number of runs which can be done (almost inevitably to one “Do-Minimum” and one “Do-Something”) and virtually prohibits proper testing of the land-use/transport interaction responses. Faster or much faster transport models allow much more to be done – and much more testing and checking to be done before committing to “production” runs. In practice, making transport models faster does mean foregoing detail. This leads to the idea of working with a “fully-detailed” transport model when appropriate, but using a much less detailed, much faster “meta-model”, calibrated to results from the full model and with the same zone system as the land-use model, in day-to-day LUTI modelling[53]. This has been successfully adopted in some projects.

Implications for testing transport interventions

7.5.11 The implications of the LUTI context for testing transport interventions in the transport model can be summarised as saying that

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[52] In UK practice, LUTI models have gone from tens of zones in the 1980s (and much of the 1990s) to hundreds of zones, sometimes upwards of 1000, in current work.

[53] For example, in the TfN NELUM model

anything that the transport model can represent can be tested in a LUTI context provided that the relevant impacts will be appropriately reflected in the data that is passed from the transport model to the land-use model.

7.5.12 In most cases, this means that the intervention can be tested if its impacts are mainly reflected in the generalised costs (or components of generalised costs) that are passed to the land-use model. This will cover many possibilities of conventional transport interventions, such as new or improved infrastructure, improved public transport services, or management measures favouring some flows as the expense of others.

7.5.13 Interventions which will **not** be reflected correctly will include

- any which are introduced into the transport modelling by directly making adjustments to demand matrices (at least unless there is reason to expect that travel will change without any resulting change in utility - see LSTF example above);
- any in which the most significant effects will be on variables which are not passed to (or are not used by) the land-use model. In the case of traffic management measures to divert traffic round and allow pedestrianisation of an historic city centre, for example, most or all models will capture the negative impact (increased generalised cost) to the diverted traffic; only some will capture the environmental improvement to the city centre except in cases where those improvements are themselves estimated in generalised cost times and input either (for preference) to the transport modelling (e.g. as reductions in generalised cost to people visiting the city centre), or (if that is not possible) as reductions in the generalised costs used by the land-use model.

7.6 Planning policies and other non-transport interventions

7.6.1 Under this heading we consider the modelling of interventions in the land-use markets. These may be intended to achieve greater benefits by integrating land-use development with transport change, but may also be aimed at other, potentially conflicting goals.

7.6.2 The modelling task is typically to forecast the take-up of the additional development with and without the transport improvement, and/or to forecast the impacts of the transport change on other land-uses with and without the planning change. Note that whilst this is (optimistically) expressed in terms of the integration of transport and land-use planning, the modelling could equally well look at potential problems if transport and land-use decisions are seriously in conflict.

7.6.3 The first thing to note is that whilst LUTI stands for “land-use/transport interaction”, many LUTI models don’t model land at all: they model building stock, usually as m^2 of floorspace of different types in each zone. Secondly, whilst they all respond to inputs describing “planning” and “planning policy” in some way, these descriptions and the ways they are used are more akin to land zoning procedures than to the more discretionary British planning systems.

7.6.4 The way in which planning inputs are prepared for and used in UK models illustrates this.

7.6.5 The "Assembly of Planning Policy Inputs" (APPI) process used to prepare inputs for TELMoS is representative of the more sophisticated approaches used in UK LUTI work. This exercise[54], which has been carried out in Scotland every two or three years since about 2003, involves collecting information from local authorities about expected development from the present year forward, ranging from developments with planning permission that are already under construction through to likely future local development plan land allocations, including expectations regarding "windfall" developments[55]. Where the information received only gives areas of land, the amount of floorspace (and where necessary the type of floorspace) that might be built is assumed by the analysts using various simple rules. The processing is carried out by site, allowing the data to be used in models with different zoning systems.

7.6.6 Where local planning authorities are able to engage properly with the exercise, such data represents an extensive inventory of the development possibilities envisaged by council officers at a particular point in time. On the other hand, it does not represent development possibilities that may emerge from or in response to new circumstances, or developments that may be resisted by the local authority but allowed on appeal. It also tends to understate or ignore demolition, or potential changes of use; if redevelopment is considered at all, it is often only the gross new construction that is counted. Note that many of these limitations are limitations of the planning system, not just of the way planning is represented in modelling. Other factors which are important to long-term outcomes which are also under-represented both in planning and modelling are the distinctions between areas, or specific buildings, where appropriate redevelopment would be welcome (e.g. inappropriate modern buildings in historic conservation areas), and those where this would be strongly resisted (the historic buildings in such areas). The effects of conservation measures will in general only appear as an absence of change, though in models which have variables for urban quality, enhancements could be represented

7.6.7 The resulting data on development possibilities is input to the model in two different ways. The quantities describing development which the authority or the analyst conside certain (usually that expected to be completed in the next few years, including buildings already under construction) are input as "exogenous development" and simply added to the stock in the relevant zone and year. Anything less certain is input as "permissible" development of floorspace by type, zone and year. (The exact terminology varies between modelling packages.) The levels of certainty are inevitably a matter of judgement.

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[54] See TELMoS18A Model Development Report (referenced earlier), chapter 6.

[55] "Windfall" sites are those which become available for development unexpectedly, typically through the closure of a business. Depending on the trends affecting its area and economy, a local planning authority may expect a number of such sites to become available over a period without knowing which ones will come up or when.

7.6.8 The model itself then forecasts how much of the permissible floorspace of each type in each zone is taken up in each year. This is a function of the overall demand for development within the model (which may be fixed as part of the economic scenario, or endogenous to the model) and the relative attraction of developing in one zone rather than another (which is a function of the endogenously calculated rent and of exogenously input development costs, both of which vary by floorspace type and zone type). In TELMoS18A and other recent DELTA models, the balance of expected rent and expected development costs provides a measure of viability which is important in determining whether development takes place or not. As a result, some inputs of "permissible" development may never be used; in other highly profitable locations, everything permitted may be developed at the first opportunity. UDM models are designed to give similar effects, but without using money variables.

7.6.9 The Scottish APPI process and TfN's comparable D-log system[56] appear to represent the most thorough exercises in representing British planning policies in LUTI models. Some models are able to make use of comparable, long-standing data collection exercises e.g. the TfL LonLUTI model[57] uses data on potential employment land developments from the London Employment Sites Database. This however only extends to the Greater London boundary; data for the surrounding area (and in the latest versions of LonLUTI, for the rest of GB) is assembled either by requesting inputs from local authorities or by processes such as "reverse engineering" NTEM data.

7.6.10 One common feature is that these models generally deal with development but not with demolition i.e. buildings stock can increase but not normally decrease. This is partly a modelling simplification and partly a matter of data availability; many local authorities neither forecast nor monitor losses of floorspace such as employment premises demolished for housing development.

7.6.11 A version of DELTA was developed with an explicit "land development model" which differs in that

- the model takes input of developable land by category rather than permissible floorspace;
- different categories can be developed for different types of floorspace, at different densities;
- the model forecasts whether and how the developable land will be taken up;

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[56] A technical report on the D-Log system as at 2020 is available at /https://transportforthenorth.com/wp-content/uploads/D-Log-I-Log-Discovery-Report-Draft_Final-clean-version.pdf; to date it has not been used for NELUM input. TfN, Transport Scotland and others are all seeking to move to more automated data collection in order to avoid sending questionnaires to local authorities. In Scotland, a prototype exercise in running an APPI process using data from local authorities' published data on planning applications and decisions, on land supply, etc, was carried out in 2021-22; the report on that exercise does not seem to have been made public.

[57] The current LonLUTI model is a DELTA application similar to the UK2070 and Highways England applications in covering the whole of Great Britain, but with additional detail in and around London and elaborate interfaces with TfL strategic transport models.

- it can also forecast redevelopment in some circumstances, if it appears sufficiently profitable to replace existing stock with new floorspace of a different type and/or at higher density.

7.6.12 This approach would appear to offer considerable benefit in terms of allowing for some of the uncertainties in planning – particularly regarding when and how employment land may be taken up. However, it has so far only been used in one UK application[58]. Note however that this version still treats "planning" as "zoning".

7.6.13 In North American practice there has been considerable activity in building microsimulation models of land-use change, forecasting development at an individual site or parcel level. Some though not all of these are LUTI models, notably PECAS[59] (which can use spatially detailed microsimulation for development processes, but is aggregate in modelling the use of the resulting floorspace and the effects of transport) and UrbanSim[60] (which in its full form is wholly micro). Site-level modelling of development can take account of a lot more detail both about what is permitted and about factors influencing the cost of development (including development fees and service connection costs which may depend on exact proximity to other developments) and its attractiveness (mountain views, or swamps with alligators) but it does not change the basic representation of planning policy - land is either designated as developable (for some types of development) or it is not[61].

7.6.14 One use of LUTI models in parts of North America (and some other regions) is to forecast the impacts of modifying (or not modifying) urban growth boundaries when the supply of land currently zoned for development is forecast to be exhausted. The resulting choices are controversial but relatively well defined. In Britain the longer-term future is altogether less clear, especially when considered in the context of transport appraisal. Even the longer-term choices considered in APPI exercises such as the TELMoS one do not look much more than 20 years ahead, in contrast with transport analyses which need to consider a 60-year appraisal period starting from an "opening year" which may itself be 15-20 years in the future. Whilst it is not usual to model the whole 60-year appraisal period (modelling 20 years and then extrapolating is more typical), there is still the problem that the period in which land-use/transport interaction may be most

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[58] That was an application of the Leicestershire and Leicester model (LLITM), about which nothing seems to have been published. The low take-up of the "land development model" version perhaps reflects the fact that most LUTI modelling is commissioned for transport planning purposes, and transport planners are sometimes reluctant to grapple with the uncertainties of the land-use planning system.

[59] See Wang, W., Zhong, M., Zhang, Y., Li, Y., Ge, J., Hunt, J. D., & Abraham, J. E. (2020). Testing microsimulation uncertainty of the parcel-based space development module of the Baltimore PECAS Demo Model. *Journal of Transport and Land Use*, 13(1), 93–112. Available at https://doi.org/10.5198/jtlu.2020.1454

[60] See https://cloud.urbansim.com/docs/general/documentation/urbansim.html

[61] The UrbanSim website referenced above recognizes as one of the limitations listed that "Land use regulations are assumed to be binding constraints on the actions of developers" and that the model cannot forecast a developer getting an exemption or waiver from zoning regulations.

important – shortly after the opening of a major scheme – is very often just beyond the period for which any reliably "real" planning policy information exists. There is also, of course, the complication that the building of major new transport infrastructure is itself likely to have an influence on planning decisions (it will become a "material consideration" that has to be taken into account).

7.6.15 One approach to these problems has been to look specifically at the question of additional development that may be permitted once the new infrastructure is in place. This is perhaps easier where there is a clear link between public transport provision and permitted densities (as in London); elsewhere, it involves a high degree of judgement. This can link neatly to the TAG concept of "dependent development" , and hence contribute towards identifying additional benefits accruing to the transport infrastructure project. There is however a risk that if the other (base case) possibilities for long-term development are understated or omitted altogether, then the demand for (and value of) the "dependent development" associated with the scheme will be overstated.

7.6.16 A more general approach is in effect to try to model planning policy in terms of where, when and how much additional development is likely to be permitted in future. This has been done in some applications of the DELTA package[62] (and maybe others) as a "planning policy response model". This allows additional development or redevelopment where there is a high demand for is, subject to certain constraints (e.g. no new development in National Parks). In TELMoS18A work for STPR2, this facility was used to allow for the possibility that significant quantities of office floorspace might fall vacant as a result of increased remote working and that, if this occurred, local authorities would generally allow it to be converted for residential use[63].

7.6.17 This last is the one known UK attempt to "model" aspects of the planning system in a LUTI model so as to allow for the uncertainties which result from its ability (and legal obligation) to respond to changing circumstances. It is still a long-way short of representing the full scope of discretion in the planning system.

7.6.18 The current position is therefore that

- all the available models largely simplify the planning system into a set of quantities defining a very basic zoning system;
- the "land development model" approach (see 7.6.11) offers a more sophisticated way of representing "zoning" that allows for some of the flexibility in the planning system;
- the "planning policy response model" approach (see 7.6.16) goes further in the same direction, allowing for some aspects of "zoning" to change in response to changing circumstances, especially in the long term where

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[62] See Dobson et al (2011): *Appraising the likely redevelopment and intensification of land uses: the role of land use and transportation models*. Paper presented to European Transport Conference, available at https://aetransport.org/public/downloads/mOzYx/5077-514ec604ae464.pdf

[63] In England such changes would generally not require local authority permission – which creates an additional complication for modelling.

transport appraisal requires modelling to forecast beyond land-use planning time horizons;

- microsimulation of development processes allows a lot more site-level data to be used, but does not change the treatment of planning in modelling.

Possible ways forward

7.6.19 The "planning policy response model" approach therefore seems promising, but is not without complications or possible controversies. Some of the present author's academic peers were rather horrified at the idea of making any aspect of "planning policy" endogenously changeable within the model, arguing that this obscures the comparison between forecasts. They are of course absolutely right that including such a response means that the impacts of a transport investment will actually be the impacts of the transport investment plus the resulting "planning policy" response, rather than the impacts of the transport investment holding "planning policy" strictly constant. This has implications for appraisal. However, it is arguably more reasonable to appraise transport investment assuming changes in planning policy that respond reasonably and systematically to changing circumstances rather than ignoring the possibility of such changes – especially if the time period under consideration is beyond the present planning horizon, and therefore the policies in effect have either to be modelled or simply assumed by the modeller. This seems especially appropriate where the model is being used to test interventions under different scenarios[64].

7.6.20 Even full use of the "planning policy response model" would still leave the model working very much as one of zoning rather than as a UK-style planning system in which there is considerable discretion in decisions both about applications and appeals. Trying to represent that discretion, and the resulting uncertainties, in a LUTI model would be very difficult in an aggregate model (i.e. where there are typically multiple developable sites in each zones) and could make it impossible to compare forecasts and to carry out appraisals in any meaningful way. A highly simplified, deterministic representation seems more necessary for appraisal to be reliable.

7.6.21 The tension between the certainty needed for appraisal and the uncertainties of "how planning really works" could perhaps be dealt with by first representing planning decisions as part of a Monte Carlo microsimulation model of development. If that microsimulation model was successful in describing observed outcomes, the resulting effects (e.g. the relative probabilities of different kinds of development going ahead in different kinds of locations) could then be incorporated into aggregate, deterministic models for forecasting and appraisal purposes – recognizing that this would depend on the discretionary aspects of the system remaining broadly constant over time.

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[64] This was the intention of the recent STPR2 work, though in the end the outcomes of the chosen strategies were not as different as expected, and only two out of six were pursued in full. See Cann et al (2021): *Modelling alternative scenarios for Scotland.* Paper presented to the European Transport Conference, available at www.etcproceedings.org

7.7 Scenario matching

7.7.1 As noted in section 3.3, “scenarios” for LUTI modelling define overall levels of change for the modelled region. In some cases, the model is also required to match externally defined totals for sub-divisions of the modelled region, or even for individual zones. The following sub-sections consider these questions in turn. We then ask what conditions that matching should be done, and whether those conditions represent the appropriate Base Case for appraisal of possible interventions.

7.7.2 Note that in some models (particularly those in Groups 5 and 7), these steps have to be taken in order to match the base year situation; in other models the base year situation is input and the focus is on matching changes over time. Group 1 models take the future Base Case situation as a given input and therefore do not require any scenario-matching work.

Matching totals

7.7.3 LUTI models can match totals in two main ways:

- where the model design includes equations that explicitly distribute the relevant totals, those totals can be directly input;
- where the model design builds up totals through a series of calculations, whether cross-sectional (e.g. an input-output model) or over time (e.g. a cumulative series of household transitions), then the inputs to the model must be the coefficients of those calculations (e.g. the technical coefficients of the input-output model[65], or household transition rates[66]).

7.7.4 Since the exogenously given scenarios are nearly always defined in terms of totals, the latter arrangement implies a need to estimate the appropriate values of the relevant coefficients that will reproduce those totals. In some cases, this is done by a pre-processor which is part of the model software; in others, it has to be done externally and directly by the model users.

7.7.5 In practice, the models which directly take in and use scenario totals tend to be relatively simple, at least in the processes that affect economic and demographic totals, if not in other ways. Where the model has multiple economic and demographic variables (e.g. jobs by sector; GVA by sector; workers by income or other socio-economic level; households by socio-economic category) the process of assembling the relevant coefficients to reproduce the target totals can become complex. This is especially true in that

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[65] i.e. units of each input needed to produce one unit of each output. In conventional input-output modelling, including the applications of such modelling in LUTI models such as DELTA, this will be the units (in value terms) of each type of goods and services needed to produce one unit (in value) of output. In LUTI models where the population is generated as part of the extended input-output framework, notably the Martin Centre models, these coefficients will include the number of households per job and the numbers of (service) jobs per household (with households and jobs typically being disaggregated into multiple categories).

[66] e.g. the proportion of two-adult, no-children households that become two-adult with-children households (i.e. start a family) in each year.

- the definitions of the externally-given scenarios may not exactly match those that are required for LUTI modelling – not least because the scenarios are often “bought in” from mainstream economic forecasting firms and are not prepared specifically for LUTI modelling;
- the externally-given scenarios may be for a different (usually larger) region e.g. for the UK economy rather than GB;
- different parts of the scenario may need to come from different sources (e.g. economic forecasts, demographic projections) which may not be perfectly consistent, and even published economic forecasts may contain implausible values (or implausible relationships between different values) that cause problems in the LUTI context;
- the externally-given scenarios may not be defined for the appropriate years, and may not extend far enough into the future; in many cases it will be necessary to interpolate for intermediate years.

7.7.6 Apart from the “headline” economic and demographic scenario variables, attention also has to be given to whether other variables which should be related to these variables will change automatically by virtue of the relationships in the model, or require other inputs to be changed in line with the scenario. For example, in TELMoS18A,

- the effect of income on car ownership is represented in the model, and does not require coefficients to change over time;
- the values of travel time, which are used in several places in the land-use model and in the associated transport model (TMfS), do not change automatically in response to income changes; new values need to be calculated and input by the users[67].

7.7.7 The details of what is required tend to differ between LUTI model applications, even of the same package, and the details of what is available in terms of external scenario forecasts vary by jurisdiction and over time, in addition to the understandable differences in client requirements across different projects. All these factors make it more difficult to fully automate the process of implementing scenarios.

7.7.8 In models where the economic and demographic scenarios are strictly fixed, it is less critical what steps are taken to match the required targets, provided they can be consistently applied in each run of the model. Where the model is able to modify the part of all of the scenarios as a result of the changes brought about by the interventions being tested, the matching to the external targets has to be done in ways that can then be modified by the model in running with different inputs. For example, sectoral GVA/worker targets may be matched by adjusting a total factor productivity (TFP) coefficient in each year and sector after allowing for other

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[67] As an example, chapter 5 of the *TELMoS18A Model Development Report* illustrates some of the complexities of such a process (https://www.transport.gov.scot/media/51913/telmos18a-model-development-report.pdf).

variables (e.g. agglomeration) that affect productivity in the scenario-matching run; then in applying the model, the TFP coefficients will be held fixed but productivity will vary in response to changes in agglomeration.

Matching local targets

7.7.9 Local targets may range from a single set of targets for one region of particular interest within a wider model (e.g. targets for the North of England, as well as for GB) down to targets for every zone in the model (e.g. from NTEM). Where only a single set of targets has to be matched, and the model is fast-running, the matching may be done by trial-and-error, with the user adjusting inputs until the match is sufficiently close; where multiple targets are involved, the task can only realistically be done if the model software has been programmed to carry it out.

7.7.10 Any such matching process depends on the choice or addition of an appropriate variables which the program or its user can adjust in order to improve the match. A common approach is to add a zonal “shadow cost” or “shadow utility” into the household or employment location function, which can be adjusted as required[68]; this is exactly equivalent to changing alternative-specific constants (ASCs) in a transport model in order to represent an otherwise omitted trend towards, or away from, the use of a particular mode (as mentioned in 7.5.9 above).

7.7.11 It is of course essential that local targets should be consistent with the overall scenario targets – otherwise the program (or the exasperated user) may fail because high local targets in one area imply negative population in another area. As at the overall level, careful attention has to be given in advance to ensure the consistency and reasonableness both of the targets that are being set, and of their relationships to other variables for which targets have not been set. A common example is that local targets may be set in terms of population; this may require controls to be applied to be applied for housing supply as well, to ensure that the population can be accommodated at reasonable densities of occupation.

7.7.12 Population targets also raise issues where, as is typical, the model works in terms of the location of households, to that any shadow utility or cost will apply to households rather than directly to numbers of persons. There is also the complication that population projections often include unspecified numbers of persons not in households[69], whilst LUTI models (and most if not all transport models) often exclude persons not in households.

Scenario-matching Case vs Base Case

7.7.13 A question which has been much debated in some aspects of practice, but is little reflected in the published literature, is the relationship of the appropriate Base Case (or Base Cases) for appraisal purposes to the externally given scenario(s) which provide the overall context. This is particularly important where – as is

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[68] One example is reported in Dobson, A C, E C Richmond, D C Simmonds, I Palmer and N Benbow (2009): *Design and use of the new Greater Manchester Land-Use/Transport Interaction Model (GMSPM2)*. Paper presented to the European Transport Conference, 2009. Available at https://aetransport.org/.

[69] e.g. persons living in care homes; military personnel living in barracks.

increasingly common – the objective of the transport interventions being appraised is partly, or primarily, to promote increase economic growth in the region of interest, or across the whole of the economy being modelled. The key questions can be formulated as

> what assumptions are embedded in the given scenario about conditions within the modelled area?
>
> are those appropriate to the Base Case for appraisal?
>
> are these consistent?

7.7.14 Common answers are that

- the given scenario assumes no change in transport conditions other than the broad macroeconomic ones that affect the money cost of transport as an input to other sectors (prices of external inputs (particularly fuel), levels of wages and productivity);
- the Base Case for appraisal (or one of the Base Cases) is often a Do-Minimum in which

  > only "committed" investments are explicitly included (though other expenditure may be implied, e.g. on maintenance or programmes of minor improvement), and
  >
  > it is expected that transport congestion will get worse, with negative effects on economic performance; so

- these are not consistent.

7.7.15 This inconsistency can be addressed, where a variable scenario model is used, by proceeding in stages:

- first creating a "scenario-matching base" of the land-use/economic model, with the transport inputs being kept constant except for changes over time in the "macroeconomic" coefficients (typically those defined by TAG parameters: vehicle operating costs, values of time and public transport fare levels); this is run to match the overall scenario targets and any local targets, as discussed in paragraphs 7.7.3 to 7.7.12 above. Typically this will be done in at least two stages, first for overall targets and then – if necessary – for local targets; the latter may also be split into further stages e.g. employment targets then population targets;
- then running the "Base Case" in which the full LUTI system is run. In this process the transport model is run with the required "Do Minimum" (or other) supply inputs, and demands calculated from the changing land uses. The outputs then reflect the forecast changes in congestion, which are fed back into the land-use/economic model and may impact both on the distribution of employment and population and potentially (after displacement effects) on the overall totals.

7.7.16 This sequence has the practical advantage that the scenario-matching base does not involve repeated running of the transport model; the required transport inputs are provided at the outset, and do not require the transport model to be fully set up for future years (only to the point where the base year network and demand can be rerun with future year vehicle operating costs, etc).

7.7.17 This whole process needs to be repeated if multiple economic/demographic scenarios are to be modelled. If different technical or behavioural scenarios within transport are to be considered (e.g. different levels of take-up in electric vehicles, and hence different rates of change in vehicle operating costs and characteristics, or changing levels of preference for walking and cycling) then there is the question of whether it should be assumed that these take place without affecting the wider economic/demographic scenarios, or whether their impacts should be considered. In the latter case they need to be treated as interventions that modify the initial Base Case.

Ex post evaluation

7.7.18 One possibility for using a model in ex post evaluation would be to take the observed situation as a given scenario, to run an appropriate model to reproduce that scenario with the transport model representing the actual changes in transport demand and conditions, and then to test the counterfactual case (i.e. without the intervention being evaluated).

7.8 Model outputs for transport modelling

7.8.1 Note that the use of outputs in appraisal is considered later, in section 7.19.

7.8.2 LUTI models may output, as potential inputs to transport modelling, one or more of

[a] microdata suitable for direct input to an activity- or agent-based model (i.e. individual household and person records);

[b] disaggregate land-use data (i.e. a sample of household/person records with weights (expansions factors);

[c] aggregate data sufficient for input to a four-stage transport model; or

[d] less data than [c] - these should probably be flagged as less than full LUTI.

7.8.3 Only UrbanSim directly produces microdata (though as noted there may be other microsimulation models under development). TIGRIS produces disaggregate land-use data for households, but not for employment. All of the other models are aggregate, and therefore need to be used with a population synthesizer if their outputs are to be used in activity or agent-based modelling or in disaggregate modelling. Such a population synthesizer is available as part of PECAS, and maybe of other packages; DELTA has been linked to TfL's population synthesizer as part of the recent integration with the MoTiON model[70].

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[70] Briefly described in Simpson, T and N Stockman (2023): *Integrating land-use, transport modelling and appraisal for London*. Presentation to 21st Transport Practitioners Meeting, available at https://www.ptrc-training.co.uk/Resources/TPM (click "Methodologies" under heading "Day Two - Session One").

7.9 Disaggregation of sectors

7.9.1 The requirement here will depend on the spatial scope and intended uses of the modelling.

7.9.2 The first issue is: does the disaggregation of economic/employment sectors in the model sufficiently separate sectors operating on different spatial scales? For example, does the sectorisation distinguish specialised financial services activities or functions that serve markets across the whole country (or internationally) from those which operate on regional or local scales? Generally this kind of distinction is not apparent in available official data, but it is possible to estimate it, for example using locational quotient methods to estimate where more specialised services are (probably) located; it makes a very major difference to model results e.g. by distinguishing the part of the professional services sector which may be significantly influenced by inter-city high speed rail.

7.9.3 The second is whether the model makes sufficient distinction between sectors that make use different proportions of passenger and freight transport.

7.9.4 A third is how well the employment sector can be matched to building types. Again, some models have created an additional segmentation of manufacturing sectors based on the occupation of the workers employed, on the assumption that a concentration of white-collar workers in a manufacturing sector implies offices (whether for management, for R&D, for administration, etc) rather than industrial floorspace. Some models allow sectors a choice of floorspace type; like other possibilities for switching between inputs, this may be helpful for marginal adjustments but could imply imply plausible results if allowed to make large changes (e.g. to put agricultural production into office floorspace).

7.9.5 A general observation is that economic models have conventionally tended to have more detail of primary and manufacturing sectors, whilst transport models seek more detail of service sectors.

7.10 Representation and disaggregation of households and population

7.10.1 It would appear that all of the models considered allow some disaggregation of households, except possibly the DCM.

7.10.2 Issues to consider include

- ability to represent households that may have more than one worker (still a common simplifying assumption, at least until recently) (how the model forecasts how many will work is considered in 7.12 below);
- do household types relate to appropriate classifications e.g. by composition (to link to household projections) and/or socio-economic status?
- ability to represent households and household compositions at different income levels (potentially with incomes from different sources) in order (amongst other things) to calculate distributional effects following Green Book guidance.

7.10.3 Scope issues:

- does the model represent residents not in households, and if so how are they represented in relevant model processes e.g. (in particular) do the relevant categories such as students contribute to labour supply?
- are part-time residents (e.g. people with second homes) and their use of housing taken into account?

7.10.4 Note that

- including the total population can make it much easier to show that the model is consistent with official population estimates and projections
- including part-time residents can make it easier to reconcile housing and households.

7.10.5 The treatment of car ownership appears to vary considerably between models. In DELTA there is a distinct car ownership sub-model, conditional on household type, income and employment levels and location. The population data output to the transport model is disaggregated by household car-ownership levels, and in the transport-to-land-use linkages those levels of ownership are used to weight the (usually very different) car-owner and non-car-owner accessibilities in calculating accessibilities for households by type. Other models generally do not mention it.

7.11 Disaggregation of workers

7.11.1 Most of the more sophisticated models allow for workers to be classified by occupation or income level as well as by the industry in which they work; in the Martin Centre and DELTA models, at least, the modelling of the interactions between home and work (residential choice conditional on workplace in the Martin Centre models, and the opposite in DELTA) is disaggregated by the socio-economic classification rather than by sector.

7.11.2 There is further disaggregation between full- and part-time workers in some models. From the point of view of labour market modelling (see below), the full-time/part-time proportions might be better derived from an endogenous forecast of hours per worker (as in RELU-TRAN) rather than being imposed exogenously as a given proportion of workers by industry. Disaggregation between male and female is required in some transport models but has not been observed in land-use models except for those based on microsimulation.

7.12 Modelling of labour markets and total employment

7.12.1 Modelling the supply of labour from households to firms is a long-standing and more or less universal feature of LUTI modelling. However, the most common approach has been that labour supply is entirely determined by the demand for labour, without reference to wages or any mechanism for balancing labour supply and demand. In the MEPLAN and TRANUS models, population itself is a simple function of the demand for labour (i.e. residents were assumed to arrive from the rest of the world if the demand for labour increased), and where they locate is conditional on where the jobs are. In earlier versions, the wage paid for each type of labour was exogenously defined as part of the economic scenario; later, it was calculated so as to maintain households at a constant standard of living, but the same assumptions about labour supply - so the wage still did not have any function in balancing supply and demand[71].

7.12.2 The UDM and DELTA models are still labour demand dominated but impose a separately defined demographic scenario. In DELTA, working-age adults shift between employment and unemployment until all jobs are filled; this is done mainly by scaling existing home:work patterns (for each socio-economic group) in line with changes in jobs and population[72]. The effect in DELTA is that if the demand for workers in one city goes up beyond the local supply, workers will in the short term be "made" to commute from elsewhere; in the medium term some households will tend to relocate closer to those jobs (if housing allows), whilst some jobs will also tend to relocate closer to workers (if floorspace allows). The potential supply of labour is controlled only at national level.

7.12.3 UDM (e.g. NELUM) is very similar but with a gradual response which allows for jobs being left unfilled in the short term. In UDM wages are not modelled at all.

7.12.4 The urban SCGE (or CUE) models differ in their treatments of the labour markets. In one the total number of working residents is assumed fixed, and wages adjust so that firms employ exactly the resulting number of workers[73]; in another voluntary unemployment is a possible choice[74] but involuntary unemployment is not considered. Models of this type assume that "working households" make a simultaneous choice of residence and workplace which is in equilibrium with the location of jobs and the wages offered there (which themselves are also changing), as well as with rents; non-working households are either ignored or located exogenously.

7.12.5 The present available models therefore fall into two groups: the mainstream LUTI models in which the numbers of working persons adjust to the numbers of jobs, which are unaffected by wages or labour supply (or only the location of jobs is affected); and the SCGE/CUE models in which the numbers of jobs adjust to the number of workers available. In the latter case, the numbers of hours worked per worker may also be variable, meaning that the model allows some adjustment on both supply and demand sides.

7.12.6 Of the models mentioned, only UDM represents unfilled vacancies, at least as a temporary effect.

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[71] Some aspects of MEPLAN and TRANUS were first developed in fast-developing cities of South America in the 1970s, where that approach worked well, and would probably have worked equally well for cities of the North of England in the mid-nineteenth century; but they do not deal well with any idea of "levelling up" or of bringing "work to the workers".

[72] Wages are modelled in most of the DELTA models but vary in response to agglomeration and other WEBs-type effects, not to reflect the balance of supply and demand.

[73] See p31 in Anas, A, and H Chang (2017) - full reference in Appendix H

[74] See p420 in Anas, A, and L Liu (2007) - full reference in Appendix H

Possible ways forward

7.12.7 For current policy questions in the UK, with an emphasis on levelling-up issues both within and between regions, and issues of labour shortages and (some) under- or unemployment, it would be very useful to have a LUTI model which would

- explicitly model unemployment, allowing for involuntary as well as voluntary unemployment (i.e. for people who cannot find work, as well as for those who are unwilling to work at present net wages[75]), with explicit modelling of whether-to-work and where-to-work choices;
- model (average) hours worked per worker (as in RELU-TRAN) with any required outputs on full-time/part-time work being derived from this;
- explicitly model unfilled vacancies[76] (and the consequences for GDP of filling them) (UDM has some representation of this);
- take into account the frictions on mobility both of labour (reluctance to move as well as housing market challenges – as in DELTA and TIGRIS) and of firms;
- adjusts one or more explicit variables (probably more complex than a simple wage by skill level and work zone, and allowing for wage stickiness) to solve the model for the partial equilibrium in any one year[77].

7.12.8 This is still some way off, though it would appear possible in the light of experience to date[78].

7.13 Supply-side choices and responses

7.13.1 One of the differences between model approaches is the degree to which the different kinds of suppliers in the model are active agents and decision-makers whose behaviour contributes to the overall forecast, or are purely passive in matching consumers' choices. This is closely linked to the treatment of prices, which are the main driver of supplier behaviour.

7.13.2 The models in Groups 1 and 2 (excluding CubeLand) tend to treat all aspects of supply as totally passive, with limited or no representation of any supply processes or constraints at all. This is not to say that supply side issues have been entirely

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[75] Note that the "more people in work" effect in TAG WEBs assumes voluntary unemployment (people are willing to take up work if net wages are increased by reduced commuting costs or times) and unfilled vacancies for those people to fill.

[76] Modelling of unfilled vacancies (as well as involuntary unemployment) is, arguably, essential to forecasting when and how net gains in employment may occur as a result of transport or regeneration/levelling-up interventions.

[77] The use of explicit variables, rather than an iterative scaling process, is needed for subsequent analysis and explanation of the results.

[78] That experience includes a variation on DELTA which DSC developed for Highways England, which had all of these characteristics except unfilled vacancies. However, it relied on a single wage variable to balance labour supply and demand, which – given the fixed demand for labour at any one point in time – turned out to be unrealistically volatile.

forgotten by the model designers; rather, their models assume a series of conditions which mean that the supply of anything relevant to the choices modelled (e.g. the supply of housing, the supply of labour) is perfectly elastic. This is most clearly unrealistic in the case of land ("Buy land, they're not making it anymore" – attributed to Mark Twain), and to building stocks which are expensive and time-consuming to change and subject to planning restrictions.

7.13.3 At the other end of the passive-active supply scale are the SCGE-based models which have explicit utility- or profit-maximising functions for the behaviour of households (as suppliers of labour), firms (suppliers of goods and services), landlords (suppliers of existing floorspace), and developers (suppliers of new floorspace). In each case these functions also take account of what is consumed and of relevant constraints (e.g. the number of hours that a worker can work in a year). Such functions for producers are also incorporated into some applications of PECAS and the PFM version of DELTA.

7.13.4 Most of the models of interest fall between the two extremes, with a focus on floorspace:

- MUSSA/CubeLand and nearly all the models in Groups 3 to 7 have (a) constraints on how much space of each type is used in each zone and (b) models of the change in floorspace supply[79];
- MUSSA/CubeLand (Group 2A) has those constraints and is exceptional in having an explicit assumption that landlords take the highest bids in auctioning space;
- DELTA (in Group 6) and RELU-TRAN (in Group 7) have, in addition, a landlord response that leaves property vacant if rents are very low (the assumption being that there is some cost (e.g. wear and tear) to having property occupied rather than vacant, and the rent needs to exceed this).

7.13.5 Note that

- all of these effects depend on the modelling of prices and rents;
- they are an important source of positive feedback effects in the model (planning responses permitting, as discussed earlier) – though the scope for changes in the intensity of use of even a fixed stock of buildings should not be disregarded.

7.14 <u>Effects of productivity changes</u>

7.14.1 Anas and Chang[80] point out that agglomeration effects on productivity work in three dimensions, or on three different margins. The first is the intensive margin of job productivity: the direct agglomeration effects of better access to economic mass (A2EM) make each job more productive, meaning that in the first instance,

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[79] The exception is LUISA2, where the model of change in floorspace supply is allowed for in the design but not implemented.

[80] See references in Appendix H

fewer workers are needed to produce the same amount of output. But it also (in competitive markets) leads to a reduction in output prices, which (generally) leads to an increase in the quantities demanded, and hence (potentially) to an increase in output and in jobs (the extensive margin). A third effect may then come into play, whereby the enhanced productivity and employment in the region in question draws in more (and better qualified) workers from the rest of the world, leading to further increases in productivity (partly through further increases in A2EM).

7.14.2 These effects, or at least the first two, are shown in the RELU-TRAN results for Paris (see Appendix H). Koopman and Oosterhaven[81] discuss the same issues in a model of the Netherlands (not a LUTI model), particularly with reference to the deficiencies of the "iceberg" treatment of transport costs. The first two effects were also observed in some of the results from the prototype DELTA PFM (see H.4.4).

7.15 <u>Calibration</u>

7.15.1 Calibration is taken as meaning

- at a minimum, setting the values of the model coefficients i.e. the values which are input to the model to specify how sensitive the modelled actors are to different variables, within a pre-defined set of equations operating on a pre-defined set of variables;
- at a maximum, revising the sets of equations and variables, as well as specifying the values of the model coefficients required for the revised equations.

7.15.2 By definition, the models we are considering involve at least two distinct equations (for households and employment location); most involve many more. Where those equations are independent of one another (as in some of the Group 1 models) then formal statistical calibration of each equation is likely to be fairly straightforward, especially as these models are mostly or wholly static in nature, which facilitates data assembly. However, all except the simplest models involve feedbacks, whether between residential location and employment location, or between through supply and demand for space (whether through price or other responses.) These immediately complicate the distinction between "dependent" and "independent" variables and make calibration, especially of responses over time, more complex. Any ideal of a "single model calibration process" giving an overall goodness-of-fit measure can be seen to be unrealistic.

7.15.3 The more sophisticated models, especially those in Groups 6, represent different processes of change that are linked through a combination of immediate and time-lagged responses. These are particularly difficult to calibrate on observed data collected directly for the region they represent. In some cases, where rich data on change over time is available, as with the official surveys of household (re)location in the Netherlands, it is possible to design the model (in that case, TIGRIS) with a view to making best use of that data. In other cases, and especially where there is a

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[81] Koopmans, C and J Oosterhaven (2010): SCGE modelling in cost-benefit analysis: the Dutch experience. *Research in Transportation Economics* vol 31 pp 29-36

requirement to implement a model for a budget that will not cover any new surveys, other approaches have to be taken.

7.15.4 This is not necessarily an undesirable situation. The table below sets out a range of possible approaches to calibration, putting the conventional idea (assumed above) of model-specific calibration on “local” data at the top (Level 1) and “professional judgement” at Level 7. The middle reaches of this table, particularly Levels 3 to 6, involve drawing on work done by others, and if this other work is high-quality quantitative research in the relevant fields of urban economics and urban geography then it offers possibilities of drawing on a wider range of work than could practically be done in the course of any single modelling study. Examples of methods used at Levels 1 to 6 are given in Table 7-3.

Table 7-2 Calibration approaches

Source: definitions based on various previous documents including *TELMoS18A Model Development Report* (reference in Table 7-4).

Level	Description	Possible examples
1	Bespoke analysis (specifically for the purposes of the model in hand) of observed data (for the same region)	Estimation of the coefficients of a household location model (e.g. coefficients of a logit model utility function including accessibility, price, environment) on data from a survey of household location choices (ideally, perhaps, from a combination of revealed preference and stated preference surveys)
2	Bespoke analysis of [i] data for another region, or [ii] of synthetic data (from microsimulation modelling)	[i] As above but using another region’s (or country’s) data [ii] Estimation of annual household transition rates (the probability that a household in one “lifestage” will move to another) from microdata output by a microsimulation model of household formation/composition
3	Matching data reported by others or evident in published reports	Matching the proportions of income spent on housing and on other goods and services to the proportions reported from government expenditure surveys
4	Direct use of coefficients estimated by others	[1] Input-output coefficients [2] Reuse of coefficients from the DfT National Car-Ownership Model (NCOM) in a car-ownership model within a LUTI model [3] Using TAG elasticities and decay coefficients for agglomeration calculations within the LUTI model
5	Reproducing elasticities or comparable sensitivities reported by others	Adjusting a household location model so that the effect of accessibility on rent (through the effect on household choices and the rent adjustment process) matches the effect of accessibility on rent estimated in a hedonic rent or price model
6	Reproducing elasticities or comparable sensitivities implied by the coefficients reported by others	Adjusting an office employment location model so that the effect of accessibility on office rents (through the effect on firms’ choices and the rent adjustment process) matches the effect of accessibility on rent estimated jointly implied by the [a] a hedonic rent model’s coefficient for the effect on office rent of distance from a central point [b] the average change in accessibility with increasing distance from that central point (as calculated in the LUTI model itself).
7	Matching to “stylized facts”, professional judgement	Could be applied to any case; note that professional judgement is not unique to this level but required in all of the above levels, whether to decide what are comparable sensitivities (Levels 5 and 6) or (at Level 1) to decide what are acceptable results e.g. whether to

Level	Description	Possible examples
		make use of coefficients that are theoretically important but not statistically significant

Table 7-3 Examples of the calibration approaches (Levels 1 to 6)

Note: examples are taken from calibration work that is (a) familiar to the author and (b) publicly reported and accessible. It is not claimed that these are necessarily the best examples of each type of calibration. References are expanded in the following table. They point to where the approach has been applied - further detail on the data/previous research used can be found in the references.

Level	Description	Example	Reference(s)
1	Bespoke local analysis	Estimation of move/stay and household location choice models using data from a national housing market survey (WBO-2002) which provided detailed data on household moves and non-moves	TXL section 5.5
2	Other bespoke analysis	TELMoS18A (and other DELTA models): default probabilities of household transitions based on probabilities estimated from a microsimulation model of household change. Those default values were then adjusted as part of the process of matching the chosen demographic scenario.)	T18A sections 9.2 and E.2
3	Matching data	[a] Inter-industry input-output technical coefficients	T18A sections 8.3 and D.3-4
		[b] Equivalent social accounting coefficients in Martin Centre models e.g. households per job and service jobs per household	Hunt & Simmonds, 1993, particularly pp 225-6 and examples pp 231040
4	Using others' coefficients	Car-ownership model – reusing the design and coefficients of the DfT National Car Ownership Model	T18A sections 9.7 and E.7
5	Matching reported elasticities etc	Rent impact of accessibility improvement reproducing an elasticity estimated by hedonic price analysis (note that in the example the impact of accessibility change on rent comes about through changes in demand and the market clearing mechanism; there is no equation directly linking rent to accessibility)	T18A sections 9.4 and E.4
6	Matching implied elasticities etc	Migration responses to employment change, using sensitivities calculated from coefficients reported in a panel data analysis of migration and other changes	T18A sections 9.3 and E.3

Table 7-4 References for Table 7-3 calibration approach examples

Abbreviation	Reference
H&S	Hunt J.D. & Simmonds D.C. (1993). Theory and application of an integrated land-use and transport modelling framework. *Environment and Planning B: Planning and Design* 20, 221-244.
T18A	DSC (2022): *TELMoS18A Model Development Report*. Report to Transport Scotland, available at https://www.transport.gov.scot/media/51913/telmos18a-model-development-report.pdf
TXL	Zondag, B (2007): *Joint modelling of land use, transport and economy*. PhD dissertation, Technical University Delft. TRAIL Thesis Series nr. T2007/4, The Netherlands.

7.15.5 It can be argued that unless the people or firms in any area of interest are (permanently) quite unusual, studies carried out over a wider area and over a longer period of time are likely to be better bases for modelling the future behaviour of those people and firms over the long term and potentially over a wider range of circumstances. Panel-type analyses (e.g. analysing change over time in a large number of spatial units (local authorities or below)) seem particularly appropriate – good examples being the studies of local economic impacts of transport by Gibbons et al[82] and of development, house prices and migration by Bramley and Leishmann[83]. Meta-studies, generalising across a wider range of locations, circumstances and possibly methods are highly desirable as bases for calibration.

7.15.6 This line of thinking leads to the conclusion that the difficulty or impossibility of calibrating more complex models by bespoke, model-specific statistical estimation on "local" data should not be seen as a major disadvantage if the design of the model is such that the models' relationships and processes can be related to those considered in wider academic research and calibrated by indirect methods such as those listed as Levels 4 to 6 above. Real local data would perhaps always be better **if** it was available, reliable, covered a wide range of circumstances and allowed for appropriate controls (e.g. to distinguish "treatment" and "non-treatment" areas), but that combination of qualities is highly unlikely.

7.15.7 If that conclusion is accepted, then

- there is no reason to prefer simple models to complex ones just because they are easier to calibrate; and
- in many circumstances there will be good reason to prefer – up to a point – more complex models which allow different processes of change – and different interventions potentially affecting those change – to be represented.

7.15.8 For example, in some cases it may be most appropriate to work with a Group 1-style model which implicit assumes that floorspace and other variables adjust can and do adjust in equilibrium with the effects of an accessibility change; but in many cases, especially when developing a LUTI model for a range of future applications rather than for the appraisal of a single scheme, it will be more appropriate to build-in the ability to explicitly represent floorspace change, and other factors driving or constraining floorspace change, thus allowing the model to take account of (for example)

- planning policies (as discussed in the section 7.6 above)
- feedback effects e.g. low-income households being priced out of areas where accessibility is improved.

7.15.9 It should also be kept in mind that successful calibration on specially assembled data can pose other problems in model implementation. One such case arose in the

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[82] Gibbons S, T Lyytikäinen, H Overman, R Sanchis-Guarner (2019): New road infrastructure: the effects on firms. *Journal of Urban Economics* vol 110 pp 35-50.

[83] Bramley, G and C Leishman (2005): Modelling local housing market adjustment in England. In D Adams, C Watkins and M White: *Planning, public policy and property markets*. Blackwell, Oxford.

estimation of a model for a major European mainland city, using an expensively prepared and very detailed data set. The exercise was very successful in coming up with a model calibration that was statistically and theoretically sound calibration (i.e. the goodness-of-fit was high, the coefficients were significant, and their signs and relative magnitudes were highly plausible); however, it proved impractical to use the calibrated model in forecasting, because the independent variables included variables which would clearly change over time but which the team had no way of forecasting. The lesson is that whilst the calibration of a largely pre-designed model may be sniffed at as "making the model fit" rather than proper model estimation, a certain level of pre-design is essential if the process is to produce a working model within a given budget and timescale.

7.16 Validation

7.16.1 Validation is taken as meaning the process of checking the performance of the model by comparing forecasts with observed data that was not used in model calibration.

7.16.2 The nature and indeed the possibility of validation depends on the type of model being considered.

7.16.3 For Group 1 models, which output differences from a given scenario for a future year, strict validation is impossible since the nature of real life is that there is only ever one version of any one year.

7.16.4 Validation is easier to envisage for the static or mostly-static models in Groups 2 and 7, and for the static parts of the models in Group 5. Firstly, it may be possible to carry out some validation of the model's performance in the base year, if base year data is available which was not used in calibrating the model. Secondly, if sufficient observed data for another later year is available, it should be possible to validate by inputting the exogenous variables for that second year and assessing how well the output (endogenous) variables match observations.

7.16.5 In Group 2, the exogenous data may be very extensive – for example, the exogenous inputs may include defining the location and quantity of a high proportion of the total employment, and the location and quantity of housing and of floorspace available for occupation by the remaining (endogenous) employment. In that case, a fairly high standard of "fit" may be almost automatic; a more appropriate test may be whether the model is "adding value" by giving a better fit to the forecast year than a "naïve" or simplistic model[84] which might have been much more quickly and easily implemented. In Group 7, at the other extreme, the models are more complex and the ratios of endogenous to exogenous variables are higher, though for validation on a second point in time it would still be necessary in some cases to input the supply of floorspace by zone and type.

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[84] A "naïve or simplistic" model would be one which distributed a total in proportion to some simple function of what would be the LUTI model inputs – for example allocating forecast year total households (from the demographic scenario) in proportion to existing housing (from the base year data) plus permissible new housing (from the planning policy inputs).

7.16.6 If that kind of validation is carried out on those models, any consideration of the findings for practical forecasting purposes has to consider not only the performance of the model, but also how reliably the required exogenous inputs could be forecast.

7.16.7 The more dynamic models (Groups 4,5 and 6) pose more challenges for validation, because in different ways they read in data for one point in time and forecast changes over time. In this case, the outputs that should ideally be validated are the forecast changes over time, not the absolute forecasts for any one year[85]. In many European and North American regions, simply copying the base year data can often give a reasonably good fit to a "forecast" year 10 years later without any modelling at all; assessing the model's ability to forecast change is therefore holding it to a higher standard. A first challenge is therefore that if these models have been calibrated on local data of changes over time, there may be no other observations are available for validation. The second problem is that it can be more difficult to supply "observed" values of some of the required inputs, especially for planning policy, where it is difficult to measure anything except outturn development retrospectively. A third problem is that data may be difficult to assemble on a reliably consistent basis; the best source of data are the Census, but this does not provide all the data required, even about households and housing, and even the Census is subject to some changes in definitions from one decade to the next[86].

7.16.8 It is often suggested that validation can be based on testing the ability of the model to forecast the response to a major transport change (such as a new or reopened railway line) using data collected from a before-and-after study (or from successive Censuses). This however is problematic:

- ad hoc before-and-after studies typically monitor only at a short period after the opening (e.g. most of the studies undertaken for light rail/tram openings), often too short for land-use responses to emerge;
- if longer-term observations (meaning, in practice, Census data) are used to try to observe longer-term responses, the number of other changes reflected in the observed data increases;
- in any case, but especially when looking at the longer term, such a study is still dependent on the model (or a model) to estimate what would have happened without the major transport change (the counterfactual situation, in the correct sense of that term).

7.16.9 A possible approach to calibration and validation of a dynamic (Group 3-6) model, put forward here for discussion, could be

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[85] The late Professor Michael Wegener was influential in putting forward this view (see 1982 reference in **Error! Reference source not found.**, p103).

[86] In fairness to ONS and others , it should be noted the collection and availability of data for land-use modelling is much better than it was 20 or 30 years ago, and generally continues to improve. See for example latest developments at https://www.ons.gov.uk/peoplepopulationandcommunity/housing/methodologies/adminbasedstatisticsforpropertyfloorspacefeasibilityresearchenglandandwales)

- the base year for the model should be that of the last Census but one (so 2011, for current UK modelling) (note that some models will also require data for some earlier years);
- the model should be calibrated using only (a) bespoke analysis (Levels 1 and 2 in Table 7-2) on data from that Census or from earlier dates/periods, and/or (b) results from other studies (i.e. Levels 3 to 6) (ideally also based on data from the base year or earlier);
- the model should then be run forward to the most recent Census (2021 for current work in England or Wales), using observed data on exogenous variables (the pattern of change over the inter-Censal period may need to be estimated for some variables);
- the performance of the model from the base year to the most recent Census can then be assessed; given the problems of measuring past planning policy this would probably need to be done on the basis both of modelling floorspace change and of inputting observed floorspace change.

7.16.10 The main differences from standard practice would be in basing the model on the last Census year but one, and in not calibrating on observed changes since the base year. This approach would need the associated transport model to be run for that year and at least one earlier year (i.e. both 2011 and 2001), though those could be done as back-casting from a more recent transport base year (so as not to conflict with the practice of basing the transport model on the most recent available data).

7.16.11 This possible approach assumes that the transport model is calibrated and validated, on data for the base year or years, before the land-use model is considered. This is feasible so long as the transport model is static, in the sense of depending on input data only for one point in time. Validating a LUTI model in which both land-use and transport components were dynamic would be more complex again[87].

7.16.12 Given the challenges involved, it is not altogether surprising that validation of LUTI models is rare.

7.17 Consistency with Green Book requirements and TAG guidance

Green Book

7.17.1 The main issue of consistency with the Green Book is probably whether the models conflict with the assumption of full employment, and hence that an intervention can only increase total (national) employment if it persuades people to work who would otherwise choose not to work, i.e. that effectively increases the labour supply.

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[87] Pointing out that using a dynamic transport model with time-lagged responses would be more complex is not to say it would necessarily be a bad idea! Apart from the potential to build on the evidence that travel and transport responses can be time-lagged and/or irreversible, it could avoid the question of whether a static model should have different responses when run repeatedly in a LUTI context rather than for a stand-alone transport-only forecast (see 7.5.5).

7.17.2 Most of the models under review work within fixed scenarios for employment, population, and households. The exceptions are

- DELTA, which can work with either fixed or variable employment scenarios and/or variable population/household scenario;
- PECAS, which would appear to offer the same choice;
- the urban SCGE models (Group 7) – but in these the number of jobs (or hours worked) has to be equal to the number of people willing to work (or collectively to work those hours), so any change in employment must be associated with changes in wages that persuade more – or fewer – people to work rather than changing a level of involuntary unemployment (i.e. the TAG mechanism for changing labour supply – (b) in the list at 7.17.7 below);
- UDM, for reasons which are not wholly clear, but may be because it allows for new or relocated job vacancies to be filled more or less rapidly

7.17.3 It would therefore appear that all the models are, or can be, run in ways which appear consistent with the Green Book approach to total employment, except UDM where (at least for the NELUM application) it is understood that a fixed national employment assumption is imposed by scaling the results. (Whether the wage decreases that the Group 7 models might forecast (e.g. in response to a high charging or marked disinvestment in transport) would be realistic is a different question.)

7.17.4 There are also some models for regions or cities (i.e. not for the whole economy) in which employment can vary endogenously. These are consistent with the Green Book if it is assumed that any gains in employment within the modelled area are losses to other areas.

7.17.5 From a LUTI modelling perspective, it would be useful to clarify the relationship between

- the Green Book assumption of full employment at a particular (but unspecified) level of incomes after taxes and commuting costs, and
- the levels of employment specified in the projections used to define LUTI modelling scenarios.

7.17.6 As mentioned in 7.7, the scenarios are often based on projections made by other economic forecasting firms. It is not clear that these always forecast full employment as specified in the Green Book.

TAG

7.17.7 The conditions for consistency with TAG are more specific: whether the models include mechanisms which coincide or overlap with the Wider Economic Impact calculations in TAG, and if so, whether those mechanisms are consistent with the TAG methods. These questions can be rephrased as asking whether the models themselves calculate

a) agglomeration effects on productivity?

b) changes in employment (and the productivity or incomes) as a result of changes in commuting costs attracting more (or fewer) people into paid employment?

c) changes in productivity as a result of changes in employment location?

d) benefits of increased output arising from transport improvements in imperfectly competitive markets?

7.17.8 Models in Groups 1 to 4 do not do any of these things; not it would appear to TRANUS, MEPLAN or TIGRIS.

7.17.9 Models in Group 7 can do all of them (category (c) because the total factor productivity coefficient varies across zones for each sector[88]).

7.17.10 PECAS can do (a) and possibly (b). DELTA can do (a) and (c).

7.17.11 All of the above are part of the "Level 3" benefits in TAG (see definitions quoted in Table 7-5). It is currently common for Level 3 benefits to be calculated using LUTI model runs which are somewhat separate from the transport model runs used to calculate the Level 1 and 2 benefits; the transport model runs may be based on separate land-use assumptions not taken from the LUTI modelling. At present, the most consistent sequence would be

- run the full LUTI model for the Base Case (see discussion of scenario-matching in 7.7);
- in each transport model year, run the transport model with the Base Case land-use inputs but the Alternative transport inputs (i.e. including the intervention to be appraised), and use the differences between Alternative and Base Cases to calculate Level 1 and Level 2 benefits;
- then run the full LUTI model for the Alternative Case, running the transport model in the appropriate years (which must be the same years as in the Base Case) using the Alternative land-use inputs as well as the Alternative transport inputs, and use the new set of differences between Cases to calculate Level 3 benefits.

7.17.12 There are still questions of whether this is fully consistent (e.g. the Level 1 time savings will not reflect any changes in congestion resulting from land-use impacts of the intervention) and whether the responses of the transport model used in the middle-stage "transport only" tests should be identical to those in the full LUTI modelling (see 7.5.5); but this would appear to be the most consistent possible given the present TAG requirements for different Levels of analysis.

Table 7-5 TAG Levels of Analysis

Source: TAG Unit A2.1 (May 2019), para 3.2.3.

Level	Definition
1	Includes impacts which assume fixed land use excluding wider economic impacts

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[88] See equation 10 in Anas and Liu (reference in Appendix H).

Level	Definition
2	Includes wider economic impacts which assume fixed land use (connectivity impacts) or do not require land use change to be explicitly quantified
3	Includes analysis in which either land use change is explicitly quantified (structural impacts) or supplementary economic modelling has been conducted

7.17.13 Dependent development is also considered in TAG and, as a land-use effect, is obviously relevant to LUTI modelling. However, dependent development is defined[89] as “developments which are expected to gain planning permission in the do-something (with-scheme) scenario but not in the do-minimum (without-scheme) scenario”. Modelling dependent development in LUTI therefore requires a change in the planning policy between the Base and Alternative Case, excluding the development from the Base Case and allowing it in the alternative. The model can then inform the decision-maker about a number of possible outcomes, e.g.

- the model may forecast that the dependent development will not occur, or will occur later than might otherwise have been assumed; and/or
- the model may forecast that the dependent development will occur, but that this will displace investment in some other development which as a result will not occur (or will only occur later than it would have done) – with a range of further consequences.

7.17.14 These outcomes may lead to revisions of what would otherwise be assumed about the benefits of the dependent development in question.

7.17.15 It should also be kept in mind that the specific guidance contained in TAG is intended to apply to “typical” small or medium schemes; the guidance recognizes that particularly large proposals which may have “transformational” effects may need different treatment, while still adhering to Green Book principles. Furthermore, many would argue that (a) programmes or policies which may give rise to many smaller schemes should be assessed collectively, and (b) whether or not a proposed scheme, programme or policy is "transformational" should be tested by analysis rather than assumed by the proposer.

7.18 Consistency with NEG

7.18.1 Section 4.8 identified five distinguishing marks of NEG:

- increasing returns to scale internal to the firm;
- imperfect competition;
- trade costs;
- endogenous firm location;
- endogenous location of demand.

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[89] TAG Unit A2.1 (May 2019) Appendix A (Glossary).

7.18.2 The five ingredients imply that some other ingredients of conventional economic modelling must already be in the mix: notably prices – otherwise increasing returns to scale will have no effect in the model.

7.18.3 In the present context, where we are looking at models that have in many cases developed from very different intellectual backgrounds to that of NEG, it seems appropriate to consider both

- a more ambitious question: which of the LUTI models under review explicitly incorporate any or all of these five ingredients? and
- a less ambitious question: which of the models implicitly capture the effects that these ingredients would be likely to have on the conventional LUTI variables of residential and employment location?

7.18.4 Given the scope of this review, all the in-scope models incorporate

- at least some endogenous location of employment (implying something about firms), and
- at least some explicit or proxy representation of the endogenous location of demand.

7.18.5 The degree to which employment location is endogenous ranges from total (any jobs could be located or relocated by the model) down to very limited (only a small proportion of employment endogenous). Where the endogenous employment is limited, it is typically restricted to services which directly supply households, mainly retailing and mainstream school education.

7.18.6 Similarly in many cases, the representation of endogenous location of demand is represented to the implied demand for retailing and education, implicit in the way that employment in these (i.e. the employment mentioned as endogenous in the previous paragraph) is influenced by the location of households.

7.18.7 It can also be argued that all the models which rely on random utility modelling for discrete choices[90] can be interpreted as representing some aspects of imperfect competition, in that the random elements typically imply differences in preferences which mean that different sources of supply are not perfect substitutes for one another, and consumers will buy inputs from all the available sources (probably in very different proportions) and not just from the one that would appear optimal given the explicit variables in the model. However, the alternative sources of supply distinguished in the model are zones rather than firms.

7.18.8 Explicit modelling of firms in LUTI modelling is another of the niche branches of research that has not become part of the mainstream. Modelling of firms is complicated by the enormous variety of firm sizes and behaviours. At one end of the scale, the set of identifiable firms includes a large number of very small ones (some of which may only operate occasionally, e.g. people with part-time occupations that the practice only on summer weekends) and a small number of very large firms, which may have large numbers of staff on a single site or

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[90] i.e. nearly all of them – see section 5.11

moderate numbers of staff spread across many sites – so in many respects the LUTI modeller has to think about establishments rather than firms. One legal entity may operate in multiple locations, or one holding company may own several subsidiaries all located on the same site. That one firm may be wholly or partially sold to another, or split into multiple parts (whether functionally, or artificially for accounting purposes), all adds to the complication of tracing firms over time. The analysis of firm's changes over time has become known as firmography; the best work linking firmography to location modelling and hence to LUTI is probably that by Moeckel[91].

7.18.9 The practical position in the operational LUTI models under review is that all of them model jobs whilst mostly noting that this is a proxy for a range of decisions made by (or imposed upon) firms that result in numbers of jobs in each location. Aspects of the models which get a little closer to modelling firms include

- versions of the UDM which nominally worked in terms of firms - though these were uniform firms all of the average size in each sector and productivity was not considered[92];
- DELTA PFM came a little closer, working with units of capacity analogous to firms, and seeking to represent increasing returns to scale.

7.18.10 A general proposition to consider further is that increasing returns to scale can only be represented in models which, at a minimum, explicitly consider the supply of goods and services. This rules out those models in which the supply of goods and services is a perfectly elastic (and implicitly, constant return to scale) response to changing demand. The Group 7 models explicitly apply constant returns assumptions.

7.18.11 A further proposition is that only models which model prices can represent the full consequences of increasing returns to scale; modelling increasing returns as reducing the demands for inputs would capture part of the story, but not the effects of allowing the producer to reduce prices, which is the mechanism by which the positive impacts of increasing returns to scale is passed on to other producers and other sectors.

7.18.12 Regarding trade costs, section 7.5 noted which models consider business travel and freight costs. Apart from considering business travel in addition to freight haulage for sectors producing goods, the only package which has been noted as explicitly allowing for other costs of trade is DELTA; however, that functionality has very rarely been used since in most contexts the obvious costs (a fixed handling cost for loading/unloading goods) had no effect on the results of the model[93].

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[91] Moeckel, R (2007): *Business location decisions and urban sprawl. A microsimulation of business relocation and firmography.* Dortmunder Beitraege zur Raumplanung, no. 126. Institut fuer Raumplanung, Univeritaet Dortmund.

[92] See section 5.3 in Swanson, J, A Davies, D Czauderna, R Harris (2006): *The impact of transport on business location decisions*. Paper presented at the European Transport Conference

[93] In effect, fixed handling costs represent an alternative-specific constant applied to all alternatives, which promptly cancelled out of the standard logit model. That would not be the case with other model

7.19 Outputs for use in appraisal

7.19.1 Which of the models can output

[a] a full set of appraisal results? (i.e. directly from the model)?

[b] data which can be used (e.g. in WITA) to calculate appraisal results?

[c] less than that?

7.19.2 The selection of the models in this review requires that they can produce outputs that can be used in WITA or similar, so [c] is by definition an empty set. We have noted above (in section 7.17) which of the models incorporate WITA-like calculations.

7.19.3 None of the models directly outputs appraisal results. Only the static adjustment models produce outputs that are calculate as changes from one situation to another, which could be constructed as appraisals. In all other cases, the models output one forecast from each model run, so appraisal requires at least the use of an appraisal program.

7.20 Experience of use in appraisals

7.20.1 Without going into detail, one can envisage a range of uses in appraisal running from the production of qualitative background information about the broad spatial and economic impacts of a proposal at one end of the scale through to the production of a formal benefit-cost analysis, presented to decision-makers, at the other.

7.20.2 Most of the experience in using LUTI in appraisal has been at the less formal end of this scale, partly because a substantial proportion of LUTI work has been carried out in jurisdictions where appraisal is less formalised than in Britain, and in particular where less use is made of benefit-cost analysis. In the USA, for example, much of the use of LUTI has been in regard to questions of whether particular plans and proposals satisfy legal requirements regarding air quality improvement.

7.20.3 Similarly, most of the earlier uses of LUTI in British appraisal were towards the less formal end of the scale and outside benefit-cost analysis, through Economic Impact Reports (in England) or Economic And Location Impact (EALI) analysis (in Scotland).

7.20.4 Most if not all of the LUTI models used in planning practice over the past 10-15 years have been used to produce inputs to Wider Economic Impact (WEI) calculations. This line of work started with research for the Eddington Review[94] and was followed by a range of applications, particularly once the WEI guidance was incorporated into TAG.

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formulations, and was not the case in the DELTA PFM prototype. The functionality in DELTA was taken from a pre-DELTA model which reflected various non-transport deterrents to international trade.

[94] Feldman, O., Nicoll, J., Simmonds, D., Sinclair, C., Skinner, A (2008): Integrated transportation land use models for calculations of wider economic benefit in transport schemes. *Transportation Research Record*, No. 2076, 161-170

7.20.5 The production of benefit-cost analysis based directly on LUTI outputs has been done with DELTA (using the associated ULTrA) software, TIGRIS, and RELU-TRAN. (The questions about the relationship between SCGE results and standard welfare calculations is left to the SCGE review or for future work.)

8 CONCLUSIONS – APPLICABILITY OF LUTI MODELS TO TRANSPORT APPRAISAL

8.1 Introduction: applicability of LUTI models to transport appraisal

8.1.1 The following sections attempt to answer the four main questions posed in the brief:

- How well are LUTI models suited for transport appraisal? What are the main limitations?
- What are the mechanisms used in LUTI models to calculate wider economic, and other wider social, benefits as in the UK government's Transport Analysis Guidance?
- How have other countries used LUTI model results in business cases?
- What is the likely cost of developing an LUTI for the UK?

8.2 How well are LUTI models suited for transport appraisal?

Meeting requirements of present TAG

8.2.1 These requirements were summarised in 6.1.4. Since they only require changes in future employment location, which the LUTI models under review can by definition supply (see 3.2), then at the most basic level those requirements can be met by any of the model packages/approaches reviewed here. It is however important to note the important assumptions or limitations affecting such outputs, in particular those listed in the following table.

Table 8-1 Limitations

#	Applies to…	Limitation
	Models that do not represent floorspace (e.g. DCM and some of other static models (including some DSCMOD applications))	These models implicitly assume that floorspace will adjust to meet demand responses driven by accessibility changes. The appropriateness of this for any particular proposal needs to be assessed.
	Static adjustment models (Group 1)	By definition, models in this Group calculate changes from a given land-use situation; therefore they cannot be used to create to forecast the initial (e.g. Base Case) future land-use pattern. Such models are therefore appropriate only where it is at least acceptable that the Base Case is taken from existing sources (e.g. NTEM) or from another model.

#	Applies to…	Limitation
	CubeLand (in full form) (Group 2A) and urban SCGE models (Group 7)	These models will explicitly assume floorspace changes subject to user-input constraints on development; they assume that the markets clear in all situations. It is therefore not clear how they will perform if there is significant market failure leading to significant numbers of vacant buildings or vacant sites in the base situation. These may be a symptom of the economic problems that the intervention being tested is intended to address, i.e. it may be that these models assume away the problem.
	Urban SCGE models (Group 7)	These models incorporate equilibrium building supply models (RELU-TRAN and some applications of CubeLand) could produce results which would conflict with planning policies, especially urban conservation policies (see discussion of the modelling of planning policy in section 7.6).

8.2.2 Some models allow for variable study area totals (variable scenarios), meaning that a model for (say) one city region may show gains in economic activity and population in response to appropriate interventions, but it will not show from where these are being displaced. To predict the distribution of displacement effects requires a model covering the “whole economy”, which for practical purposes can reasonably be taken as Great Britain. The issues of modelling the whole of GB and at the same time providing sufficient spatial detail in the areas of most interest are discussed in section 7.2. Note also the issues of whether a multi-regional model should be simply a larger application of a city model, or requires different mechanisms to drive forecasts of change (also discussed in section 7.2).

8.2.3 The remaining models (Groups 3, 4, 5 and 6) will all provide a dynamic assessment of the required effects including supplying the requirements of TAG place-based appraisal but all will be limited in consideration of levelling-up effects if their study area is less than national. It should also be noted that there are some issues around the TAG expectation that changes are, by default, assessed relative to NTEM scenarios:

- some of these models (notably Groups 5 and 7) have to be fitted to the base year situation (rather than taking it as input, as Groups 3, 4 and 6 largely or wholly do); it may not be possible to achieve a perfect fit to the observed data, in which case the forecasts may be starting from a somewhat unrealistic situation;
- some but not all of the models can be constrained to match NTEM scenarios under appropriate conditions (see discussion about scenario-matching in 7.7).

8.2.4 These issues do not affect the validity of the changes forecast by the models, but may raise questions about combining wider impacts estimated from these models with conventional transport benefits from stand-alone transport models based directly on NTEM scenarios.

8.2.5 The significance of the dynamic element is only partly in the explicit ability to meet the formal requirements of the appraisal process for multi-year forecasts (or, conversely, to save the user from doing post-model adjustment to obtain a profile of impacts and benefits over time from a static model representing only a single year or a couple of years at long intervals). The underlying theory and mechanisms of the model, the issues of calibration, and the degree to which the models can convince "consumers" of model results are all critical.

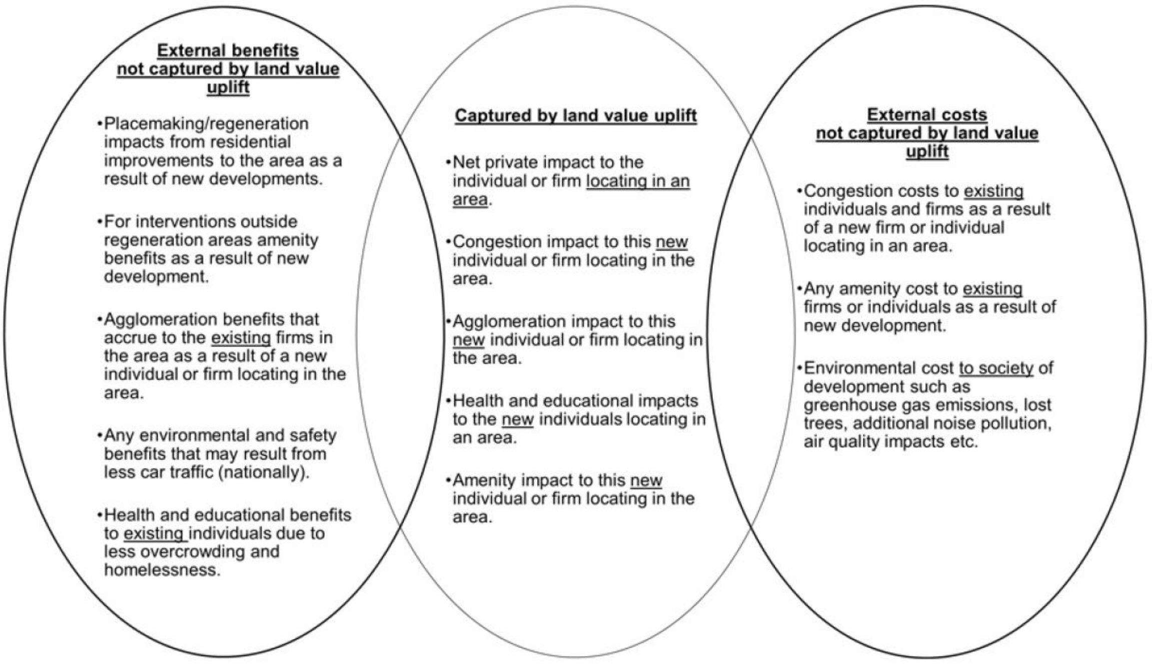
Meeting DLUHC requirements

8.2.6 The recent TAG Conference presentation by Andrew Charlesworth-May suggested greater collaboration on appraisal between DfT and DLUHC, and mentioned the possible use of LUTI models to support DLUHC appraisals. It therefore seems appropriate to consider the implications of DLUHC guidance for LUTI modelling.

8.2.7 The DLUHC appraisal guidance has recently been revised, putting more emphasis on area effects rather than solely on effects within individual regeneration sites. However, land value uplift remains at the centre of the revised DLUHC approach, as illustrated in Figure 8-1 below. Any LUTI modelling used in support of a DLUHC appraisal would therefore need to forecast property market rents or prices, whether as a contribution to calculating land value uplift or, at a minimum, to distinguish property market effects from other effects and to take account of feedbacks (such as the possibility that some households or firms may be priced out of an area that is successfully regenerated – the perennial "gentrification" issue).

Figure 8-1 DLUHC appraisal guidance: framework for assessing externalities

Souce: DLUHC appraisal guide, 31 March 2023, Figure 6 (p100)



8.2.8 The DLUHC guidance also points out that "there is no additional economic benefit from government providing support for *an outcome which would have happened anyway* (though, there may be if *the outcome happens quicker*, is of a better quality than it otherwise would be or it redistributes outcomes to different places, e.g. in need of levelling up)"[95]. With reference to the italicized points, note that

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[95] para 2.23, p15; italics added

- the need to consider what would have happened anyway (the deadweight issue) is assisted by modelling approaches (except those in Group 1) which can model two versions of the future, the Alternative differing from the Base only by including the intervention to be appraised;
- the need to consider how quickly the intervention has its effect (if any) points towards the use of dynamic models.

8.2.9 If LUTI models are to be used to contribute to DLUHC-guided appraisals, they therefore need to include property market rents or prices and at least some explicit dynamic element. This points to a requirement for models in the lower right-hand parts of Figure 5-1 (see p36), i.e. in Group 4, 5, or 6.

8.2.10 In addition, it seems appropriate to note that whilst the DLUHC guidance includes several dozen references to "displacement", it makes very little reference to the question of **where** people or economic activity may be displaced from. The exception is paragraph 4.32, which states that

"For very large interventions which are likely to have significant regional impacts a structural economy model [i.e. supplementary economic modelling, in DfT terms] could be used to examine impacts including:

- The total change in land prices for new developments across all areas; and
- The spatial and sectoral distribution of economic activity."

8.2.11 The implication for any modelling undertaken to meet this requirement is that the modelled area needs to be wide enough to give an unconstrained and unbiased view of where displacement effects will be incurred. As for the displacement effects of major transport changes, this points towards models which are national in scope with more detail in the areas of concern.

Other approaches

8.2.12 In addition to the distinct DfT and DLUHC approaches centred on time and cost savings and on land value uplift respectively, there are other approaches to appraisal which try to integrate formal cost-benefit analysis of land-use (or regeneration) and transport interventions into a single system. Known examples include the methods proposed by Zondag and colleagues in the Netherlands[96] and by the present author and colleagues in the UK[97]. Practical applications of these have been linked to the TIGRIS and DELTA models respectively, though the approaches are not necessarily tied to these. The Zondag method concentrates on accessibility measures (see the description in G.1.9); the Simmonds approach (AbLUTA) is more comprehensive and draws upon the dynamic and price/rent

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[96] Geurs, K, B Zondag, G de Jong, M de Bok (2010): Accessibility appraisal of land-use/transport policy strategies: More than just adding up travel-time savings. *Transportation Research Part D* 15 382–393.

[97] Simmonds, D C (2023): *Accessibility-based land-use/transport cost:benefit analysis for place-based appraisal*. Paper prepared for European Transport Conference, Milan. See also the same author's presentation to the TAG Conference, October 2023.

aspects of the kinds of modelling available in Groups 4, 5, and 6, including feedbacks through developer responses.

8.2.13 Both of the above approaches rely on calculating measures of accessibility, based on the generalised costs of travel and on the distribution of land-uses, relating them to households, and uses changes in those measures to calculate benefits to residents (and other agents) in each zone. They therefore calculate transport benefits (and other benefits and transfers, in the AbLUTA case) in terms of the land-using activities to whom they accrue. A potential alternative is to identify and measure any benefits that arise in the land-use system that are not simply transformations of transport benefits, to express those benefits in terms of generalised costs per trip, and to add them into the conventional transport cost-benefit analysis.

8.2.14 DfT has recently commissioned further research into the merits and demerits of these and other approaches, so no further comment is offered here.

Conclusion

8.2.15 In the interests of “joined-up government” it seems essential that future LUTI modelling should be capable of meeting the requirements of both DfT and DLUHC, and (as far as these can be foreseen) of any joint appraisals that the two Departments might undertake in future. Together, these require modelling of property markets and preferably of other prices, and of developer responses; for modelling developer responses, and for consideration of the timing of impacts and benefits, dynamic modelling is needed. They also require the ability to look at the national picture of displacement effects as well as local detail in areas of direct concern. All this points towards models of Groups 4, 5 and 6, particularly Group 6 for the explicit dynamics and multi-level spatial structures that these offer. Group 7 might also be appropriate if run in an explicit dynamic form with working development responses, and if the model run times are acceptable.

8.3 How are wider economic and social benefits calculated in LUTI models?

8.3.1 The first part of the answer is that none of the LUTI models considered are designed directly to calculate wider economic and social benefits. They calculate forecasts which can be compared to calculate benefits (of all kinds). The range of benefits that can be calculated depends on the type of model used. Some models forecast variables which directly correspond to specific benefits: for example, fully-specified DELTA models calculate dynamic agglomeration effects which correspond to those defined in TAG (though there may be differences in detailed calculation, such as the use of logsums for averaging over modes).

8.3.2 Even for common variables such as forecasts of employment and of households and/or population, the methods vary widely. The one common element is the use of random utility models for discrete choices such as, most obviously, the choice of zones by locating agents. These are nearly always logit models, though there are good reasons why alternative formulations should be considered where practical, to make more realistic assumptions about the unobservable variations in agents' preferences[98].

8.4 How have other countries used LUTI model results in business cases?

8.4.1 No reports have been found of other countries using LUTI models for business cases. Further questions could be asked in countries where land-use effects (such as dynamic agglomeration) are considered in appraisal.

8.5 What is the likely cost of developing an LUTI for the UK?

8.5.1 There are at least four models which cover at least the whole of England & Wales:

- two simple ones (QUANT and DCM)
- two complex ones (LUISA and several applications of DELTA, including the Highways England model).

8.5.2 Note that all of these are largely or entirely LUMIT models; providing the transport side of a GB or UK LUTI model, whether for LUMIT modelling or full LUTI modelling, is as probably as much a practical challenge as the land-use/economic modelling.

8.5.3 The answer to the question about cost would therefore depend on

- whether the Department wished
  - to start from one (or more) of these existing models – and if so, how much it might wish to change the existing design;
  - to commission a new application of another existing model package, or
  - to commission a wholly new model design (and hence wholly new software);
- the level of calibration required (see Table 7-2, page 85), and whether new survey work would be required to support that calibration (i.e. to pursue Level 1 of Table 7-2).

8.5.4 The use of 2021/2022 Census data needs to be considered. It should soon be possible to obtain the detailed bespoke tables needed for LUTI model implementation, but it will be important to consider the impact of the Covid-19 pandemic (or of the measures taken to limit the pandemic) on the data, especially in terms of what it says about whether and where people were working at the time. Whilst it would seem remiss not to use 2021/2022 Census data at all, it may be better to define any new/improved model as being based on estimates for the first

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[98] See the discussion in de la Barra, Tomas R. and Liu, Liu (2023): *Discrete Choice Revisited: Attribute Correlation, Marginally Decreasing Perception of Utility and the Multiplicative Error Term*. Available at SSRN: https://ssrn.com/abstract=4394983 3

"new normal" post-pandemic year, say 2023, or possible for a pre-pandemic year with a simplified treatment of what happened during the pandemic[99].

8.5.5 To give some indications of the actual figures that might be involved:

- a short programme of model runs using one of the existing "national" models in LUMIT form would probably cost somewhere in the £10-50k range, **excluding** the production of the transport cost changes to feed into the model;
- a full update of one of those models (to a base year circa 2021/2022) and revised calibration would probably cost something in the lower £100Ks;
- a wholly new national model (i.e. a new model design to an original specification), or a complete rebuild of an existing model with recalibration using data from a major new survey or surveys, would cost more than £1milllion.

8.5.6 The corresponding timescales would probably be of the orders of

- two or three months (less for the simpler models, if staff are available);
- around a year;
- several years.

8.5.7 These figures assume consultancy contracts for the work. It would of course be possible for the Department to develop a new model in-house, either entirely from scratch or incorporating components licensed from others, or to pursue a mixed approach. The relative merits of such approaches, and other issues of organization and management for successful modelling, are beyond the scope of this review, but some relevant references are noted in the box below..

Box 8:1 Conditions for successful modelling - notes

Another whole review could be written about the managerial, cultural and organizational conditions that seem to be necessary for technically successful and practically useful modelling projects in or for government. Some relevant material noted in this review includes sections of the following papers:

(1) Putman, S H (2010: DRAM residential location and land use model: 40 years of development. In F Pagliara, J Preston and D Simmonds (eds) (2010): *Residential location choice: models and applications*. Springer-Verlag, Heidelberg;

(2) Saujot, M, M de Lapparent, E Arnaud, E Prados (2016): Making land use – transport models operational tools for planning: from a top-down to an end-user approach. *Transport Policy* 49 20–29;

(3) Donnelly, R, W J Upton, B Knudson (2018): Oregon's Transportation and Land Use

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[99] The latter approach was taken in TELMoS18 (see references earlier) but – to avoid confusion – note that it was implemented before the 2022 Scottish Census had taken place.

Model Integration Program: A retrospective. *Journal of Transport and Land Use* vol 11;

(4) the recommendations for creating a ”self-sustaining modelling environment” in Rolf Moeckel, Carlos Llorca, Ana T. Moreno & Matthew Bediako Okrah (2018) Trends in integrated land-use/transport modeling: An evaluation of the state of the art. *Journal of Transport and Land Use* vol 11.

8.5.8 Any discussion of modelling for planning and appraisal purposes rapidly comes to “horses for courses” argument, that models should be appropriate to the questions that need to be addressed and should not be developed until those questions are defined. But in order to enter a winner in a horse race, you need to have the horses in the stable in advance, not to start breeding the ideal one for the course just before the race. For questions of transport planning, political timescales of decision-making tend to be much faster than model development timescales, so models need to be developed before there is a specific need for them[100].

8.5.9 Another reason for not following the “horses for courses” adage is that it is possible to consider two or more quite distinct models being integrated into one overall model in order to provide a versatile model capable of meeting a wide range of requirements. A number of examples of such integration are mentioned in this review, including

- the higher-level model in TIGRIS,
- the higher (macrozone) level models in DELTA (a spatial input-output model of the economy, and a separate migration model responding to “push” and “pull” influences over time),
- the lower-level microsimulation of development processes in some applications of PECAS,

all of which are integrated with zonal-level aggregate models, with differences in dynamics. Care is needed in integrating different modelling approaches, but combining the best models of different variables at different levels can offer both theoretical and practical advantages.

8.5.10 The greater the investment in new or improved modelling, the more important it would be for the Department to plan for the continuing use and support of the model, including the continuing staffing of the work. As noted earlier, until recently there has been little movement of land-use modellers between different model packages. The most widely-used of the existing UK packages are supported by some dozens of professionals with experience in that particular package. A new and distinctly different model would need to create its own labour supply.

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[100] The Oregon TLUMIP experience highlights the value of having models available that can be applied to new and urgent issues as they emerge. So did experience in the UK during the Covid-19 pandemic: amongst other contributions, the DELTA Strategic National Model (see Appendix G.2) was used as one of the analytical methods in a study into the need for food banks, and the TELMoS/TMfS system was used to test the degree to which the combination of lost/furloughed jobs and remote working would reduce the demand for public transport. For TLUMIP see Donnelly, R, W J Upton, B Knudson (2018): Oregon’s Transportation and Land Use Model Integration Program: a retrospective. *Journal of Transport and Land Use* vol 11.

8.5.11 As a general comment, given the diversity of model designs available, is that the Department should consider investing in two or three complementary modelling approaches rather than putting all its money on one horse. “Complementary” might for example mean a sophisticated (if inherently slow) “research” model based on best academic methods together with a fast “policy” model for application to forecasting and appraisal, with the outputs of the “research” model being used to calibrate the “policy” model[101].

8.6 Concluding points

8.6.1 The overall situation is that a wide range of LUTI models – by definition, all those considered in this review – are capable of providing the **present minimum** requirements of TAG appraisal for forecasts of land-use change resulting from transport change – though some would require post-processing of their results to maintain fixed employment totals, and - whilst some produce annual series of results – others would require some post-processing to convert outputs for one or a few points in time into a profile of impacts over time suitable for inclusion in the calculation of NPV etc.

8.6.2 If considering **only** those formal requirements, the choice between the models must depend not on the appraisal requirements but on criteria applied to the modelling itself –in particular, whether it is specified that the model must explicitly forecast through time, or alternatively, that it must explicitly find an overall equilibrium situation. This is arguably the central and most debatable question in LUTI modelling, and one on which there are some strongly held opinions amongst those working in the field. The present author’s view on this remains broadly that which he reached in the mid-1990s:

- the time-lags in land-use change are of fundamental importance both to understanding and to appraising the impacts of proposed interventions, and as such have to be modelled explicitly;
- microsimulation is intellectually attractive as a means to implementing this, but the resulting stochastic variation in data and results (see 3.9 above) makes it impractical for use in decision-making contexts;
- the modelling therefore needs to be aggregate; for the aspects of the model which represent many simultaneous transactions competing for resources (usually property markets, labour markets) it is justifiable and practically helpful to model these as converging to separate but inter-related short-term equilibria, which (if well-designed) ensure that there is a unique and internally consistent[102] solution to the model in each year and a set of

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[101] This suggestion is not new; it was made to the Department by the present author and colleagues at the conclusion of the SimDELTA project (see G.2.28). Since coefficients or elasticities could be produced specifically for LUTI modelling purposes, this would correspond to Level 4 of the calibration approaches in Table 7-2.

[102] One of the issues with dynamic models that do **not** converge to an equilibrium solution in which supply and demand are balanced is that they may leave excess demand which is not accounted for but cannot be removed from the totals, e.g. households which are living in the modelled area but not allocated to a zone,

variables (rents, wages) which help to explain how and why that solution has been reached.

8.6.3 The combination of an explicitly dynamic process (and, as a result, a time-series of results which can be feed into the year-by-year sequence of impacts to be appraised) with short-term supply-and-demand effects in individual markets has considerable advantages in terms of intuitive appeal to many professionals and decision-makers, including the ability to link to research in other disciplines studying processes of urban and regional change.

8.6.4 For other forms of appraisal, whether developing a joint DLUHC-DfT appraisal or applying an alternative land-use/transport appraisal framework such as AbLUTA, the outputs of models that represent rents, wages and (ideally) other prices are required, implying a need rather than just a preference for models which more fully represent market processes; the arguments for dynamic modelling remain the same.

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although housing is available and affordable to them. This was a major issue in the experimental "dynamic housing market" version of DELTA (see G.2.27), but appears to be common in fully dynamic models that do not have an iterative process to solve such questions – though it is often only documented, if at all, in a footnote.

APPENDIX A GROUP 1: STATIC ADJUSTMENT MODELS

A.1 Dynamic City Model[103]

Description

A.1.1 The Dynamic City Model (DCM) is a “static adjustment” land-use model recently developed by Arup. It is a “static adjustment” model in that it reads in

- Base Case land-use data;
- Base Case generalised cost matrices;
- Alternative Case generalised cost matrices.

A.1.2 From the inputs it calculates

- first the changes in accessibilities due to the changes from Base to Alternative generalised costs, and
- secondly the changes in land-use i.e. it calculates
  a) the Alternative distribution of households, as the Base Case distribution modified by the changes in accessibility to employment, and
  b) the Alternative distribution of employment, as the as the Base Case distribution modified by the changes in accessibility to households or to other employment.

A.1.3 The model can be applied to one or more future years, which are independent of each other. Note that

- the user has to supply the Base Case land-use data – it is an input to, not an output of, the DCM;
- the Alternative Case transport model run has to be produced using the Base Case land-use data (i.e. it is an entirely conventional transport-modelling Alternative Case with unchanged land-use assumptions)
- the calculations of Alternative household and employment distributions are independent of each other – there is no interaction between them (though presumably this interaction could be achieved by manually copying the Alternative land-use data back into the Alternative accessibility calculations).

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[103] Information from discussion with Dr Csaba Pogonyi, Arup. The DCM is described in Pogonyi, C and A Moreno Pelayo (2023): *The Dynamic City Model.* Paper presented to the to 21st Transport Practitioners Meeting, available at https://www.ptrc-training.co.uk/Resources/TPM (click “Models & Methodologies” under heading “Day One - Session One”).

A.1.4 There is no consideration of land or building supply constraints, or of rents; implicitly, the model assumes that building supply (and if necessary planning policy) will adjust to some degree implicit in the data on which the model's sensitivities to accessibility are calibrated. There is a facility to assume a specify period for the (linear) build-up of impacts.

A.1.5 The DCM is similar in concept to the former DSCMOD package[104], though DSCMOD also had the option for households and employment to compete for given supplies of land or floorspace (which could be fixed or exogenously varied between Base and Alternative), using an iterative rent feedback mechanism to apply the space constraint[105].

A.2 PIRANDELLO

History

A.2.1 PIRANDELLO was developed in the early 2000s as a model of the Paris and the surrounding region (the Ile de France). Whilst at least one website[106] presents it as a package rather than as a one-off model application, the only application elsewhere seems to have been for Lyon (see Kryvobokov reference below).

A.2.2 There seems to be only one conference paper available on the internet describing it[107]. There are some links to the original French reports but none of them work.

Description

A.2.3 It can be briefly described as a further elaboration of the DCM and DSCMOD approach. For the residential model, the further elaboration is that households' location choice is assumed to be based on a utility function which combines

- a "domestic comfort" term, which is itself a function of the floorspace and the income that the household would enjoy in each zone;
- accessibility to employment (using a logsum measure);
- the residential cost (housing price and tax); and
- a constant for the zone/income-level combination, representing all other variables (assumed fixed).

A.2.4 The "domestic comfort" term is similar to equivalent measures used in MEPLAN/TRANUS and subsequently in PECAS and DELTA; PIRANDELLO is also similar to these models in measuring housing supply by floorspace area and

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[104] Full disclosure: DSCMOD was developed by the present author and colleagues.

[105] The DSCMOD source code has long since gone to the great repository in the sky, but the calculations can be implemented in the DELTA package (or, if the rent feedback is not required, very easily implemented in a spreadsheet once the accessibility measures have been calculated).

[106] https://piron-consulting.com/fr/pirandello-un-nouvel-outil-daide-a-la-decision/

[107] Jean Delons, Nicolas Coulombel, Fabien Leurent (2008*): PIRANDELLO an integrated transport and land-use model for the Paris area*. Paper prepared for the 88th TRB Meeting, available at https://hal.science/

allowing floorspace per household in each zone to vary as a function of the demand to locate there.

A.2.5 The employment location model is likewise slightly more elaborate than the DCM or DSCMOD equivalents.

Documentation

A.2.6 Apart from the Delons et al paper referenced above, two reports in French have been identified but not obtained:

- *Modèle Pirandello d'équilibre général urbain* (in French). Cofiroute, Sèvres, France, 2009.
- Piron V., and Delons J. PIRANDELLO: un modèle d'équilibre urbain (in French). In *Modéliser la ville: Formes urbaines et politique de transport* (Antoni J.-P., ed.), Economica, Paris, 2011, pp. 78–118.

A.2.7 The following reference has also been found but not pursued:

- Kryvobokov, M., Chesneau, J.-B., Bonnafous, A., Delons, J., & Piron, V. (2013). Comparison of Static and Dynamic Land Use–Transport Interaction Models: Pirandello and UrbanSim Applications. Transportation Research Record, 2344(1), 49–58. https://doi.org/10.3141/2344-06. The abstract[108] is interesting:

  The paper addresses comparability of two urban modeling frameworks: the static equilibrium Pirandello and the dynamic disequilibrium UrbanSim. The two frameworks, though conceptually different, contain some common features in their transportation and land use models. An empirical test includes the long-term effect of an urban toll implementation in the Lyon urban area in France. The conclusion is that the static and the dynamic urban modeling frameworks, despite their fundamental differences, can generate, in most cases, comparable empirical results, which are intuitively logical and can be used for policy scenario evaluations.

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[108] https://www.semanticscholar.org/paper/Comparison-of-Static-and-Dynamic-Land-Use%E2%80%93Transport-Kryvobokov-Chesneau/4fbc82b1ec00956caa860b3d4197cc4ed37acf44

APPENDIX B GROUP 2: SIMPLER MODELS

B.1 Introduction

B.1.1 This group is represented here by the long-standing ITLUP family of model and the very recent QUANT model. Numerous other models have been built to similar designs; some are mentioned in section B.4.

B.2 ITLUP, METROPILUS, TELUM AND G-LUM

History[109]

B.2.1 ITLUP was originally developed by Dr Stephen Putman in the early 1970s. His consultancy firm, S.H. Putman Associates, subsequently developed the same or very similar models as a software package embedded in a Geographic Information Systems (GIS) environment: METROPILUS (Metropolitan Integrated Land Use System). The Federal Highway Administration (FHWA) sponsored the development of a METROPILUS derivative, TELUM (Transportation Economic and Land Use Models), to provide a user-friendly land use model for small- and medium-size Metropolitan Planning Organizations (MPOs).

B.2.2 G-LUM is a freely available, open-source land use model developed by Dr. Kara Kockelman and her graduate students at the University of Texas at Austin. The model is based on Dr. Putman's documentation of ITLUP equations. G-LUM was coded in MATLAB to provide transparency, try to corroborate TELUM's results, overcome TELUM's zone size restrictions, and enhance land use density predictions. G-LUM can be run either within the MATLAB software or as a stand-alone GUI application.

B.2.3 The mathematical formulation of the model (described below) has changed relatively little over its half-century history, apart from the addition of lagged terms changing it from a wholly-static to a semi-static design, and an additional module to calculate and constrain densities. The main focus of continuing work seems to have been on usability including simple interfacing to standard data sources (e.g. the United States Census) and automated calibration routines using available, local data. As a consequence of the emphasis on data availability, the dimensions of the models have been kept small – no more than a handful of household types (e.g. income quartiles) and a similar number of employment sectors, and restricted

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[109] Mainly from https://www.caee.utexas.edu/prof/kockelman/g-lum_website/homepage.htm. A more detailed history of the DRAM (residential) component is given in Putman, S H (2010): DRAM residential location and land use model: 40 years of development and application. In F Pagliara, J Preston, D Simmonds*: Residential Location Choice - Models and Applications*. Springer, Berlin.

numbers of zones (except in G-LUM). This emphasis is reflected in the number of applications – over 40 applications of the residential component[110] by 1988.

2.2.4 For brevity, these four packages are collectively referred to here as "the ITLUP models".

B.2.5 The concluding section Professor Putman's paper in Pagliara et al (2010) contains a thoughtful discussion of the problems of land-use modelling in practice, and how these contributed to ITLUPs evolution to METROPILUS and subsequently TELUM[111]. Many of the difficulties he records ring equally true from British practice.

Description

B.2.6 The documentation of the model describes many of the coefficients simply as coming from the automated calibration process, without discussion of their meaning. Some of the following is therefore the present author's interpretation.

B.2.7 The ITLUP models are based very much on the highly influential Lowry model design[112], in that households are located around the workplaces where they are employed, and employment is located around the households which supply its labour and demand goods and services. There are no explicit markets or price variables of any kind; the allocation processes are based on entropy-maximising concepts, themselves derived from statistical mechanics i.e. estimating the statistically most likely distribution of individual units (gas particles, households, jobs) given certain total quantities. The present ITLUP model works in five-year steps with a number of time-lagged terms.

B.2.8 A proportion of households of each type remain located from one modelled year to the next. {equation (1) in G-LUM} The number of households to be located is calculated as a function of the employment in each zone, and these households are distributed conditional on workplaces, so the number of households located in each residence zone is the sum of the number allocated from each workplace. The allocation from each workplace depends on a function of the time and/or cost of commuting and a zonal attractiveness term which combines

- a function of the vacant land and the land already developed for residential use in the zone
- the previous household mix in the zone.

B.2.9 It would appear that the household mix component is intended to capture other unmodelled effects regarding the attractiveness or otherwise of the zone.

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[110] ISLGUTI Phase 1 report, p435 – see reference in Appendix J

[111] Putman, S H (2010: DRAM residential location and land use model: 40 years of development. In F Pagliara, J Preston and D Simmonds (eds) (2010): *Residential location choice: models and applications*. Springer-Verlag, Heidelberg

[112] More precisely the Garin-Lowry design, which was the first to locate households from individual workzones to residential zones; the original Lowry design located households on the basis of accessibility to employment in general.

B.2.10 Employment is located in a very similar way i.e. distributed to workzones conditional on household location. Although "basic" employment is explicitly mentioned in the G-LUM documentation, there does not appear to be any difference in treatment between "basic" employment and the "service" types, unless this is achieved by the choice/calibration of coefficient values[113].

B.2.11 The land allocation model is mentioned in G-LUM documentation as calculating densities. It is assumed that households and employment (of all kinds) compete for land, unless constraints on households or employment numbers are introduced to limit this competition. There is no immediate feedback from densities to location (and no rent or other price terms); there is a time-lagged feedback link from the density calculations to residential location (see Figure 1 in G-LUM documentation). Since the documentation does not even indicate the expected signs of the coefficients, it is not clear how that feedback will operate: one might expect positive feedback, e.g. that if the proportion of developed land occupied by employment increases, the zone will become less attractive for residence.

B.2.12 The work-home relationships forecast by the residential component (DRAM) in the original ITLUP model (i.e. the number of households working at *j* and located at) were used to calculate commute trip matrices which were applied directly in the ITLUP transport model. However, the ITLUP models do not require the use of their own transport model, and it is not clear that the more recent packages offer one.

B.2.13 TELUM has a multi-regional input-output model component; however, this appears to be a stand-alone pre-processor used in preparing the employment inputs to the main model.

Sources/documentation

B.2.14 TELUM documentation is available at

- https://www.telus-national.org/documentation/index.htm

B.2.15 G-LUM documentation is available at

- https://www.caee.utexas.edu/prof/kockelman/g-lum_website/G-LUM_Code_Documentation.pdf

2.2.16 The following papers describe recent applications:

- Shuhong Ma, Yan Zhang and Chaoxu Sun (2019): Optimization and Application of Integrated Land Use and Transportation Model in Small- and Medium-Sized Cities in China. *Sustainability,* vol 11(9).
- Anju Sebastian, Sangeeth K (2020): Integrated Transportation and Land Use Planning Model: A Study on Traffic Congestion in Urban Areas. *International Journal of Science and Research*. This paper is of questionable value in itself, but mentions applications in Singapore, Adelaide, and Ahmadabad.

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[113] The Leeds model LILT was closely related to ITLUP. The description of LILT in DSC & MEP (1988) hints that the differences between sectors in LILT were implemented by coefficient values.

B.2.17 For an ITLUP/UrbanSim comparison see Jennifer Duthie, Kara Kockelman, Varun Valsaraj, Bin (Brenda) Zhou (2007): *Applications of integrated models of land use and transport: a comparison of ITLUP and URBANSIM land use models*. Paper presented at the 54th Annual North American Meetings of the Regional Science Association International, Savannah, Georgia.

B.3 QUANT

Sources/documentation

B.3.1 The following is based mainly on

- Batty, M and R Milton (2021): A new framework for very large-scale urban modelling. *Urban Studies*, vol 58.

Background

B.3.2 QUANT is described as “essentially a sketch planning tool to enable ‘what if?’ type impacts on the location of employment, population and transportation infrastructure to be evaluated”.

Design

B.3.3 The mathematical design of QUANT is very similar to that of the ITLUP models i.e. households are located around jobs and vice versa; differences are that QUANT is entirely static (all relationships are simultaneous, as in the original version of ITLUP) and there is no consideration of land supply, nor apparently of any other zonal constraints.

Application

B.3.4 As for other ITLUP-like models, QUANT has been developed with an emphasis on usability, but taking an entirely different approach: rather than providing a model which can be readily implemented and calibrated in any city, it is implemented as a single, publicly-accessible, web-based model for the whole of Great Britain, with a large number of zones (8,436) which is sufficient to make it reasonably useable for any urban area in the three nations[114]. There is at present no provision to refine the calibration for any one region[115].

B.4 Other models in Group 2

B.4.1 Numerous other models comparable to ITLUP etc have been built by academics and as ad hoc applications by practitioners. Whilst there are variations, the common characteristics are largely or wholly static structures, spatial interaction approaches whereby residents are located around their jobs and service employment around residents; and prices/rents that are either exogenous or

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[114] The alpha version is available at http://quant.casa.ucl.ac.uk/

[115] There is a rather mystifying message on the main screen asking the user to “calibrate the transport parameter before running the model” - but giving no clue as to how to do so.

adjusted over time by a hedonic price model, rather than by an iterative process to clear the markets at each modelled point in time. There is generally a “basic employment” category which is assumed to be fixed in location and distribution at each point in time, and it is nearly always implicit that each household has one and only one worker. Relatively recent examples along these lines include a cluster of related models for various cities and regions in Italy, some of them using the model name STIT[116], and several models of Santander (Cantabria)[117]. To what extent these are based on common software is not clear.

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[116] e.g. Nuzzolo, A, P Coppola (2005): S.T.I.T.: A system of mathematical models for the simulation of land-use and transport interactions. Paper presented at the European Transport Conference, Strasbourg.

[117] See Coppola, P, Á Ibeas, L dell’Olio, R Cordera (2013): LUTI Model for the Metropolitan Area of Santander. *Journal of Urban Planning and Development*, vol 139; or the sections on the model for Santander in Cordera, R, Á Ibeas, L dell’Olio, B Alonso (2017): *Land Use–Transport Interaction Models*. Taylor & Francis

APPENDIX C GROUP 2A MUSSA/CUBELAND

C.1 History

C.1.1 MUSSA stands for *Modelo de Uso de Suelos de Santiago*[118] (land-use model of Santiago). It was originally a stand-alone model for the city of Santiago de Chile, developed as a research tool by Professor Francisco Martínez and colleagues at the University of Chile from the early 1990s onwards with support from various agencies of the Chilean Government.

C.1.2 Around 2002 the MUSSA software was licensed to Citilabs Inc and was packaged as CubeLand, part of the broader Cube transport modelling suite. The packaged version is designed to facilitate integration with transport models built in other Cube package products, though it it not necessarily exclusively used with these. The Cube suite, including CubeLand, is now distributed by Bentley Systems.

C.2 Description

C.2.1 The standard form of MUSSA is a static equilibrium model of household and employment location and of floorspace supply.

C.2.2 The household and employment location processes are characterised by

- a bid-rent function describing how much each household or employment unit is willing to pay (i.e. “bid”) to locate in each relevant type of space (e.g. each type and size of dwelling, for households) in each zone;
- a mechanism by which property owners (landlords) choose the highest bids for each unit of space.

C.2.3 “The location problem [that MUSSA solves] assumes that real estates are allocated to the highest bidder by auctions and that market equilibrium is attained by the condition that all agents are located somewhere, therefore, supply satisfies demand. This auction process produces rents for each real estate in the market and simultaneously defines levels of satisfaction (benefits) to located agents at equilibrium”[119]. The model design is based on explicit recognition that location choices involve both competition among agents in the markets for space, and strong externality effects between location outcomes which affect that competition – for example, changes in employment location affect the spatial distribution of demand for housing, even if the legal (planning) constraints on the use of different

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[118] https://ingcivil.uchile.cl/investigacion/software-mussa

[119] From Introduction to Martínez, F and P Donoso (2010):The MUSSA II land use auction equilibrium model..In F Pagliara, J Preston, D Simmonds (eds): *Residential location choice - models and applications*. Springer, Berlin.

space types means that there is no direct interaction between the different markets involved (constraints are imposed to ensure that activities only occupy types of floorspace where they are permitted).

C.2.4 The MUSSA model assumes (like others) that all the agents in the system make optimal choices but that there are differences in preferences, unknown to the analyst, which introduce an apparently random element; appropriate assumptions about the distributions of the unknown elements allow the model to be solved as a system of logit models. The properties of the logit model also allow the highest bids to be calculated analytically (i.e. by an equation[120]) rather than by comparing values in a list (the model works in an aggregate form, so there is no list of individual bids at any point in the calculations).

C.2.5 The design of the model allows the supply of floorspace to be adjusted as part of the static equilibrium solution In this case, property owners adjust the quantities and types of floorspace that they supply so as to maximise their profits (after taxes and subsidies) subject to constraints representing the land-use planning system. The supply and demand for floorspace are therefore adjusted simultaneously so as to find an overall equilibrium. Alternatively, the supply of floorspace can be taken as given at each point in time, and the modelling of floorspace supply can be treated as changing over time. The supply of floorspace can also be fixed by the user to allow what-if forecasting of the consequences of land-use change.

C.3 Application

C.3.1 The application of MUSSA was for Santiago, Chile. Information provided by Bentley Systems indicates that nearly a dozen CubeLand applications have been developed in the USA, and a similar number elsewhere in the world. To date the only application in the UK is for the Greater Lincoln area[121].

C.4 Documentation

C.4.1 Further documentation of the development of MUSSA/CubeLand (not necessarily applicable to the current form of the model) is contained in papers including the following[122]:

- Martinez, F. (1992). The bid-choice land-use model: an integrated economic framework. *Environment and Planning A*, volume 24, 971-885.
- Martínez, F. y Donoso, P. (2001). Modeling Land Use Planning Effects: Zone Regulations and Subsidies. *Travel Behavior Research, The Leading Edge.* Editor: D. Hensher, Pergamon-Elsevier, 647-658

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[120] Equation (7) in Martínez and Donoso (2010) op cit.

[121] Minta, P and J Tijong (2021): *Bid-Rent location Modelling – Greater Lincoln Land Use Model*. Paper presented to the European Transport Conference, available at https://aetransport.org/

[122] These references have mainly been provided by Bentley Systems, and have not necessarily been consulted for the present report

- Martínez, F. Donoso, P. (2001). Modeling Land Use Planning Effects: Zone Regulations and Subsidies. *Travel Behavior Research, The Leading Edge.* Editor: D. Hensher, Pergamon-Elsevier, 647-658.
- Martinez, F. Henríquez, R. (2007), "The RB&SM: A random bidding and supply land use equilibrium model" *Transportation Research Part B* 41 632–651.
- Martinez, F. Aguila, F. y Hurtubia, R. (2009). The constrained multinomial logit: A semi-compensatory choice model. *Transportation Research Part B*, 43, 365-377.
- Bravo, M. Briceño, L. Cominetti, R. Cortés, C. Martínez, F. (2010). "An integrated behavioral model of the land-use and transport systems with network congestion and location externalities" *Transportation Research Part B* 44 584–596.
- Martínez, F.J. y Donoso P. (2010). The MUSSA II Land Use Auction Equilibrium Model. In F Pagliara, J Preston, D Simmonds (eds): *Residential location choice - models and applications*. Springer, Berlin

C.4.2 The solution algorithm at least partly set out (for one version of the model) in

- Martínez, F and R Henríquez (2003): *A stochastic land use equilibrium model.* Paper presented to the 10th International Conference on Travel Behaviour Research (IATBR), Lucerne[123].

C.4.3 Links (supplied by Bentley Systems) for other recent applications include

- Model of the Western Cape (South Africa): https://www.bentley.com/wp-content/uploads/CS-Western-Cape-Province-LTR-EN-LR.pdf, https://roadsonline.com.au/new-travel-demand-model-for-western-cape-province-with-bentley-systems/
- Paper on the Western Cape application: https://repository.up.ac.za/handle/2263/82348
- Application in Western Australia: https://australasiantransportresearchforum.org.au/wp-content/uploads/2022/05/ATRF2021_Resubmission_116-1.pdf.

C.5 Comparable models

C.5.1 The RURBAN model[124], developed in Japan, is very similar to MUSSA/CubeLand.

C.5.2 A comparable model has been built for Berlin. This model was calibrated using Census microdata supplemented with an imputed income variable; the method[125] is

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[123] https://archiv.ivt.ethz.ch/news/archive/20030810_IATBR/martinez.pdf

[124] Miyamoto K, Kitazume K, Sugiki N, Vichiensan V (2007*): Applications of RURBAN Integrated with a Transport Model in Detailed Zone System*. Paper presented to the World Conference of Transport Research.

potentially of interest for any future UK model calibration attempting to use Census (or other) data that lacks essential variables such as household income.

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[125] Heldt, B, P Donoso, F Bahamonde-Birke & D Heinrichs (2018): Estimating bid-auction models of residential location using census data with imputed household income. *Journal of Transport and Land Use* vol 11

APPENDIX D GROUP 3: SYSTEMS DYNAMICS MODELS

D.1 UDM and MARS: history

D.1.1 UDM and MARS are the main or only UK examples of urban models developing using Systems Dynamics tools.

D.1.2 They were both developed, apparently independently, in the early 2000s, the respective leaders being John Swanson at Steer (then SDG) (UDM) and Paul Pfaffenbichler at the Technical University of Vienna (MARS). MARS has been extensively used by University of Leeds ITS (in particular, by Professor Simon Shepherd) for research and training purposes.

D.2 UDM and MARS: descriptions

D.2.1 "The dynamic feature means that the UDM does not reach a convergence nor an equilibrium stage. Instead, the UDM provides a trajectory of growth for population, jobs and land/floorspace development. The UDM adapts approaches used by Forrester in his "Urban Dynamics" work, published in 1969[126]. The main example is that of "table functions" to represent non-linear relationships, the output of which are multipliers, pivoting around 1, which are used to modify the growth rate or decline rate of stocks over time, such as the number of households or businesses in a zone." (UDM Overview, 1.4)

D.2.2 Descriptions of both UDM and MARS emphasise feedback effects and the use of causal loop diagrams both to document the model's working and apparently in graphical programming of the models (using VenSim). (The presence of feedback loops, both positive (self-reinforcing) and negative (self-limiting), is not by any means unique to these models – see for example DELTA.) In the UDM case, no equations seem ever to be published, though the model is described as working in terms of sets of "attractor variables". The attractors for households are described (UDM Overview, 1.8) as

- housing stock age;
- housing availability;
- access to employment.

D.2.3 "The mathematical forms of these 3 attractors mean that they return multipliers pivoting around 1 as a function of a measure of the attractor. If it is a pull factor, for example, a zone with very good access to employment, the multiplier will be larger than 1. If it is a push factor, for example, a zone with few available houses,

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[126] J. W. Forrester (1969): *Urban Dynamics*. MIT Press, Cambridge (Mass.)

the multiplier will be less than 1. Zonal numbers of households and population can increase or decrease given different transport conditions and availability of household premises" (UDM Overview, 1.9).

D.2.4 Some points to note from this:

- each of these variables can be a "push" or "pull" factor depending whether the value is less than or more than 1 (this is different from the more common usage whereby some variables are "pull" factors and others are "push" factors)
- there are no money variables, and it is not clear how competition for housing is resolved;
- the implication seems to be that one calculation can increase or decrease the number of households in a zone (in contrast with models where moving out and moving in are different processes, or households explicitly move between zones);
- it is not clear how the combined attractor variables operate over zones e.g. what happens if (due to a boom in employment and housing construction) all zones have positive attraction variables on all three variables.

D.2.5 For the MARS model, in contrast, some equations are reported, and there is some modelling of rents, though these are not apparently connected to any other variables. Household location is modelled by a logit model of relocation from zone to zone, given an initial calculation of the number of moves from zone *i* and considering accessibility, average income of households and rent in each possible destination zone *j*. (Note that as in some other models including DELTA, it is assumed that a household's income may change as a result of location to a different zone – in contrast with workplace-dependent models (such as TRANUS) where income is predetermined at the household's (one) given workplace.

D.2.6 UDM incorporate its own transport model but can be used as a land-use model with inputs from other models; the same is believed to be true for MARS. Note that in Steer materials, "full UDM" means LUTI operation and "UDM Lite" means LUMIT operation (UDM Overview, 1.3).

D.3 MARS: documentation

D.3.1 The first reference is the original design:

- Pfaffenbichler, P (2003): *The strategic, dynamic and integrated urban land use and transport model MARS (Metropolitan Activity Relocation Simulator): Development, testing and application*. Doctoral dissertation, Fakultät für Bauingenieurwesen, Technischen Universität Wien. Available at https://www.researchgate.net/profile/Paul-Pfaffenbichler/publications
- Pfaffenbichler P, Emberger G, Shepherd S (2007): The integrated dynamic Land Use and Transport model MARS. *Networks and Spatial Economics*.
- Pfaffenbichler P, Emberger G, Shepherd S (2010): A system dynamics approach to land use transport interaction modelling: the strategic model

MARS and its application. *System Dynamics Review* vol 26, No 3 (July–September 2010): 262–282

D.4 UDM applications: documentation

Table D-1 References to UDM applications

Source: communication from Steer Group

Application	Reference/hyperlink
West Yorkshire model	Various conference publications e.g. Swanson, J, L Rognlien, A Davies, D Czauderna, C Triadou (2008): Evaluation and impact of agglomeration economies: application to Leeds City Region. Paper presented at the European Transport Conference Roberts, P, J Swanson (2011): Developing and applying a dynamic land use transport interaction model to identify an outcome-based transport strategy and investment plan for Leeds. Paper presented at the European Transport Conference https://www.steergroup.com/projects/our-urban-dynamic-model-secures-ps1bn-funding-transport
Northern Economy and Land-Use Model (NELUM) (Transport for the North)	See chapter 3 in https://transportforthenorth.com/wp-content/uploads/Future-Scenarios-Technical-Annex.pdf. For the technical context (TfN's Analytical Framework, of which NELUM is a part) see https://transportforthenorth.com/blogs/the-analytical-framework-a-new-digital-asset-for-the-north/ or https://transportforthenorth.com/wp-content/uploads/JSnape-Presentation-TfN-Analytical-Framework.pdf
Transport for the South East Scenarios Planning (SEELUM)	https://transportforthesoutheast.org.uk/app/uploads/2020/11/Scenario-forecasting-summary-report.pdf https://transportforthesoutheast.org.uk/app/uploads/2020/11/Scenario-forecasting-technical-report.pdf
High Wycombe "Decision Informing Tool"	https://high-wycombe-udm.netlify.app/#/
Midlands Connect (proof of concept)	https://mcseeksyourview.steergroup.com/#/
South & West Yorkshire; Milton Keynes (demonstration models for DfT)	Swanson, J, A Davies, D Czauderna, R Harris (2006): The impact of transport on business location decisions. Paper presented at the European Transport Conference

APPENDIX E GROUP 4: MICROSIMULATION DYNAMIC MODELS

E.1 IRPUD and related models[127]

E.1.1 The IRPUD model was developed over a long period, starting in the 1970s, by Professor Michael Wegener and colleagues at the University of Dortmund, and subsequently at the consultancy firm Spiekermann & Wegener Urban and Regional Research. Its key characteristics were a focus on the processes of urban change over time, drawing on urban microeconomic theory but moving away from the equilibrium modelling framework (see Wegener et al, 1986). It was also the pioneering example of using microsimulation to deal with the heterogeneity of households and household choices. It is therefore noted here in Group 4 but is equally significant to Group 6 (multi-level dynamic models).

E.1.2 The IRPUD model itself has been extensively used in a wide variety of research projects, but was considered too complex to reapply to other cities[128]. Its importance in practice has been through its influence on the designs of the DELTA, TIGRIS and UrbanSim packages, all of which are described later.

Related models

E.1.3 A range of successors to the IRPUD model have been built, mainly in academic research. (References for all of these are in **Error! Reference source not found. Error! Reference source not found.**.)

E.1.4 MASTER was a model design and software developed by Professor Roger Mackett, initially at the University of Leeds and subsequently at UCL; it was applied to Leeds and London. It made more extensive use of microsimulation, and was an important influence on STUDI and on SimDELTA (see below). STUDI was a more recent microsimulation model of London developed as a PhD project by Aris Christodoulou at UCL

E.1.5 SILO is of interest in that it exploits the use of microsimulation to deal explicitly with multi-worker households, with budget and time constraints (e.g. no household locates where any of the household's workers would commute more than 200 minutes per day [household location is conditional on workplace(s)]) and a clear distinction between constraints and preferences, which is considered important in a situation where many low-income households face high housing costs, high

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[127] References for this section are in **Error! Reference source not found.**Table E-1, page 121.

[128] In consequence, in Phase 2 of ISGLUTI, no attempt was made to apply IRPUD to another city, but both LILT and MEPLAN were applied to Dortmund making use of the IRPUD database. For ISGLUTI see Appendix J.

transport costs and high energy costs. However it only deals with residential location[129]. FABILUT is a further development of SILO that also locates jobs, giving a full LUTI model. Both have been developed by a consortium of German universities.

E.1.6 In addition to these academic studies, the SimDELTA model was developed by DSC for DfT around 2007 by implementing microsimulation processes (strongly influenced by MASTER) to replace most of the household and individual choices in a DELTA application previously developed for South and West Yorkshire (see references in table below). The overall conclusion of the project was that microsimulation can be highly appropriate for research purposes, but that research should be used to inform the design and calibration of more conventional (i.e. aggregate, deterministic models) which are more appropriate to the policy-making and appraisal.

References

Table E-1 IRPUD and related references

Model	Reference
IRPUD	Wegener, M (1982): Modelling urban decline: a multilevel economic-demographic model for the Dortmund Region. *International Regional Science Review,* vol 7 pp 217-241.
	Wegener M, Gnad F, Vannahme M (1986) The time Scale of Urban Change. In: Hutchinson B, Batty M (eds.) *Advances in Urban Systems Modelling.* North-Holland Amsterdam, pp145-197
	Spiekermann K and Wegener M (2018): Multi-level urban models: Integration across space, time and policies. *Journal of Transport and Land Use* vol 11 pp 67-81
	Spiekermann K and Wegener M (2011): From Macro to Micro - How much is too much? *Transport Reviews*
	Wegener, M. (2018): *The IRPUD Model*. Spiekermann & Wegener Urban and Regional Research Working paper 18/01. Available at https://www.spiekermann-wegener.de/en/category/pub?p=ks
MASTER	Mackett, R (1990): *MASTER model*. Report to TRRL. Mackett, R (1992): *Micro simulation modelling of travel and locational processes: testing and further development*. Report to TRRL. Mackett, R (1993 *Micro simulation modelling of travel and locational processes: results.* Report to TRRL.
STUDI	Christodoulou A (2010): STUDI: *A model to simulate the impacts of new metro lines on urban development in London*. PhD dissertation, University College London

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[129] In most other models (that do not have explicit travel time constraints), commuting more than 200 minutes each way each day would be unlikely but not impossible – and indeed there would be nothing in most model designs to prohibit workers from commuting more than 12 hours each way each day if the incentives (e.g. high salaries and cheap but very attractive housing) made that trade-off attractive. But note also that in many cases, it is not necessarily assumed that workers commute every day (and in at least one model there is specific representation of remote working).

Model	Reference
SILO	Moeckel, R (2015): Modeling constraints versus modeling utility maximization: Improving policy sensitivity for integrated land-use/transportation models. Proceedings of the 94th Annual Meeting of the Transportation Research Board, Washington D.C.
	Moeckel, R (2017): Constraints in household relocation: Modeling land-use/transport interactions that respect time and monetary budgets. *Journal of Transport and Land-Use*, vol 10 pp 211-228
	Kii, M., Vichiensan, V., Llorca, C., Moreno, A., Moeckel, R. and Hayashi, Y.: Impact of Decentralization and Rail Network Extension on Future Traffic in the Bangkok Metropolitan Region, *Sustainability*, 13, 13196, 2021. (https://doi.org/10.3390/su132313196)
FABILUT	Ziemke, D, N Kuehnel, C Llorca, R Moeckel, and K Nagel (2021): FABILUT: The Flexible Agent-Based Integrated Land Use/Transport Model. *Journal of Transport and Land Use* vol 15
ILUTE	Miller, E J, J D Hunt, J E Abraham, P A Salvini (2004): Microsimulating urban systems. Computers, Environment and Urban Systems 28 (2004) 9–44
SimDELTA	DSC (2007): Household location modelling: Final Report to Department for Transport, Part 1. [This part of the Final Report includes the conclusions, which are also summarised in the following reference.]] Feldman, O, R Mackett, E Richmond, D Simmonds and V Zachariadis (2010): A microsimulation model of household location. In F Pagliara, J Preston, D Simmonds (eds): Residential location choice - models and applications. Springer, Berlin. Simmonds D, Feldman O, Christodoulou A, McDonald M (2011*): Latest developments in the SIMDELTA model: investigation of stochastic variation and development of disaggregate car ownership model*. Paper presented to the CUPUM Conference, Lake Louise, Alberta. [Note that this reports further work after the end of the DfT contract.]
	Moeckel, R (2015): Modeling constraints versus modeling utility maximization: Improving policy sensitivity for integrated land-use/transportation models. Proceedings of the 94th Annual Meeting of the Transportation Research Board, Washington D.C.

E.2 UrbanSim : history

E.2.1 The development of UrbanSim was started by Paul Waddell and colleagues, then at the University of Washington, in the mid-1990s in a project for the city of Oahu, Hawaii, and subsequently continued in an application to the cities of Eugene-Springfield, as part of the Oregon TLUMIP programme[130]. Information on the UrbanSim Inc website suggests that it is in use in approximately 20 cities in the USA, and in about half a dozen in the rest of the world; it is not clear how active these all are. A considerable number of academic applications have been carried out in a variety of countries.

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[130] see Donnelly, R, W J Upton, B Knudson (2018): Oregon's Transportation and Land Use Model Integration Program: A retrospective. *Journal of Transport and Land Use* vol 11.

E.3 UrbanSim : description

Introduction

E.3.1 UrbanSim models are wholly microsimulation-based, dynamic models of urban change within a city or city region. They are controlled to exogenously prepared economic and demographic scenarios. Like TIGRIS and DELTA, it consists of a series of modules which are implemented in a fixed sequence for each modelled year. The spatial units are either zones, grid cells or parcels.

E.3.2 UrbanSim does not a transport model but has been connected to a wide variety of transport model. Since its output is microdata (records for individual households, persons and jobs) it can be connected directly to an activity-based model without the need to apply a population synthesizer first.

Employment transition model

E.3.3 The employment transition submodel predicts new jobs being created within or moving to the region,or the loss of jobs in the region. Employment is classified into employment sectors based on industrial sector codes. Aggregate forecasts of sectoral employment are exogenous inputs to the model. It is the job of the transition model to add or remove jobs to match this exogenous input. The employment transition model integrates exogenous forecasts of aggregate employment by sector with the UrbanSim base-year database by computing the sectoral growth or decline from the preceding year, and either removing jobs from the database in sectors that are declining, or queuing jobs to be placed in the employment location choice model for sectors that experience growth. In cases of employment loss, the probability that a job will be removed is assumed proportional to the spatial distribution of jobs in the sector. The jobs that are removed vacate the space they were occupying, and this space becomes available to the pool of vacant space for other jobs to occupy in the location component of the model. New jobs are not immediately assigned a location. Instead, new jobs are added to the database and assigned a null location, to be resolved by the employment location choice model.

Household transition model

E.3.4 The household transition submodel predicts new households migrating into the region, or the loss of households emigrating from the region, or the net increase in households due to individuals leaving an existing household to form a new one. The submodel accounts for changes in the distribution of households by type over time, using an algorithm analogous to that used in the employment transition model. In reality, these changes result from a complex set of social and demographic changes that include aging, household formation, divorce and household dissolution, mortality, birth of children, migration into and from the region, changes in household size, and changes in income, among others. In this application, the household transition model, like the employment transition model described above, uses external control totals of households by type to provide a mechanism for the user to approximate the net results of these changes. Control totals may be segmented by variables such as household size, age of head, and income. As in the employment transition case, newly created households are added to a list of movers that will be located to buildings by the Household Location Choice Model. Household removals, on the other hand, are accounted for by this model by removing those households from the housing stock, and by properly accounting for the vacancies created by their departure.

Household relocation model

E.3.5 The household relocation submodel predicts the relocation of households within the region each simulation year. For households, mobility probabilities are based on a binary logit model of relocation estimated off of recent movers in the synthetic population. This reflects differential mobility rates for households at different life stages. The combination of new and moving households serves as a population of households to be located by the household location choice model. Housing vacancy is updated as movers are subtracted, making the housing available for occupation in the household location models. The relocation submodel is configured as a choice model.

Household tenure choice model

E.3.6 The household tenure choice submodel predicts whether each mover household chooses to rent or own a housing unit each simulation year. This tenure submodel is structured as a choice model using a binary logit specification, and uses household characteristics to predict the relative probability of owning vs renting.

Employment location choice model

E.3.7 The employment location choice submodel predicts the location choices of new or relocating jobs. In this model, we predict the probability that a new job will be located in a particular DA. The model is specified as a multinomial logit model, with separate equations estimated for each employment sector. For both the employment location and household location models, we take the stock of available space as fixed in the short run of the intra-year period of the simulation, and assume that locators are price takers. That is, a single locating job or household does not have enough market power to influence the transaction price, and must accept the current market price as given. The variables included in the employment location choice model are drawn from the literature in urban economics. For example, we expect that agglomeration economies influence location choices.

Household location choice model

E.3.8 The household location choice submodel predicts the location choices of new or relocating households. In this model, we predict the probability that a household that is either new (from the transition component), or has decided to move within the region (from the household relocation model), will choose a particular location. The form of the model is specified as multinomial logit, with random sampling of alternatives from the universe of DAs with vacant housing. For both the household location and employment location models, we take the stock of available space as fixed in the short run of the intra-year period of the simulation, and assume that locators are price takers. That is, a single locating household does not have enough market power to influence the transaction price (or rent), and must accept the current market price as given. The model architecture allows location choice models to be estimated for households stratified by a range of demographic variables, such as income level. Alternatively, these effects can be included in a single model estimation through interactions of the household characteristics with the characteristics of the alternative locations. For the DA-level application of the model, households are stratified by 4 income categories, 3 age categories, and 2 tenure categories (rent, own) for a total of 24 model segments.

Demand-Price Equilibration

E.3.9 Real estate prices are updated by a demand-price equilibration algorithm. UrbanSim uses real estate prices as the indicator of the match between demand and supply of space at different locations and with different building types, and of the relative market valuations for attributes of housing, non-residential space, and location. This role is important to the rationing of land and buildings to consumers based on preferences and ability to pay, as a reflection of the operation of actual real estate markets. Since prices enter the location choice utility functions of households, for example, an adjustment in prices will alter location preferences. All else being equal, this will in turn cause higher price alternatives to become more likely to be chosen by residential occupants who have lower price elasticity of demand. Similarly, any adjustment in prices alters the preferences of developers to build new construction by type of space. Real estate prices are modelled using a price-demand equilibration algorithm that utilizes gradients from the location choice model to estimate market-clearing prices. The equilibration algorithm we use reflects the impact of aggregated individual demands at each DA on prices, and the resulting effects of the altered prices on individual choice probabilities.

Real estate developer model

E.3.10 The real estate developer model simulates the location and type of new residential development at the DA level. The form of the model is specified as multinomial logit, with random sampling of alternatives from the universe of DAs with remaining capacity for residential units. New residential unit locations are statistically modelled as a function of explanatory variables, including price, accessibility, and neighbourhood characteristics. DA-level zoned capacities are respected, and data on environmentally protected land such as the GGH green-belt influence outcomes. New residential units are added to the simulation when vacancy rates drop below threshold levels, and then those units are placed by the fitted location choice models. The model is stratified by residential unit type: single-family, apartment, and other.

Other aspects

E.3.11 UrbanSim is a stochastic microsimulation, and therefore each run of the model will to some extent give different results from identical inputs. This is usually addressed by carrying out repeated runs of each forecast and averaging the results. The number of runs required typically depends on the degree of detail in which the results are going to be considered.

E.3.12 UrbanSim was for a number of years an open-source product as part of the wider OPUS platform, and a significant number of applications around the world were started (though not necessarily completed) by researchers seeking to make use of it. That version may still be available, but the newer version licensed by UrbanSim Inc is claimed to be much faster in operation[131].

E.4 UrbanSim : documentation

E.4.1 There is a considerable published literature about UrbanSim and its applications, though some of it is significantly out of date regarding the model design. UrbanSim Inc have confirmed that the following reference describes the current version of the model design:

- UrbanSim Inc (2021): *Smart Planning Infrastructure for Canada – Modelling Report*. Draft Project Report to Canada Mortgage and Housing Corporation.

E.4.2 The description of UrbanSim above is based on that document, which also describes the application of the model at both a fine zonal level (Canadian Census Dissemination Area (DA) level – average population 400-700 persons) and at parcel level. The corresponding report on model application:

- UrbanSim Inc (2021): *Smart Planning Infrastructure for Canada – GGH Case Studies*. Draft Project Report to Canada Mortgage and Housing Corporation

contains a series of demonstrations of the impacts of planning policy changes in Toronto, some of them linked to transport investments (but not appraising those developments).

E.4.3 In Europe, at least two distinct models of Brussels have been implemented[132], and two models of the Ile de France (Paris) region. Various other academic exercises have used the software.

E.4.4 There seem to be few examples of UrbanSim being used in the appraisal or assessment of transport proposals; certainly the original motivation for UrbanSim development was very much to do with the environmental (especially air quality) impacts of urban development as influenced by transport investment. One for Paris has been identified, looking at the Tangentielle Nord, but the available reference[133] only covers the implementation and calibration of UrbanSim and the linked transport model METROPOLIS (not to be confused with METROPILUS). Some discussion of the impact of the Grand Paris Express (Métro extension) project has been published[134], but much less than a full assessment.

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[131] Communication from UrbanSim Inc, October 2023

[132] see pp 3-4 in Jones, J, D Peeters, I Thomas (2016): Scale effect in a LUTI model of Brussels: challenges for policy evaluation. *European Journal of Transport and Infrastructure Research*, vol 17(1).

[133] De Palma A., Nguyen-Luong D., Motamedi K., Picard N., Moyano J., Waddell P., Chauchard-Lefevre F., Ouaras H. (2005): *Modèle dynamique de simulation de l'interaction Urbanisation-transports en Région Ile-de-France: Application à la Tangentielle Nord*. Rapport intermédiaire de la 2ème phase. IAURIF/THEMA

[134] Picard, N, A de Palma (2019): Le modele UrbanSim, u outil d'analyse prévisionelle de la localisation des emplois et de la population. J-C Prager (ed): *Le Grand Paris Express: les enjeux économiques et urbains*. Economica, Paris.

E.5 Variants and similar models

E.5.1 One version of UrbanSim provides a compromise between the purely hedonic price formation and the equilibrium price formation of most aggregate models[135].

E.5.2 An American product called URBANLY is being developed to provide a modelling system comparable in scope and overall approach to UrbanSim. It is reported to have reached proof-of-concept stage. The key differences from UrbanSim claimed by the developers[136] include

- instead of having a fixed sequence of submodels implemented in turn in each year, URBANLY is developing a form of "multithreaded" design whereby interactions happen as time progresses (e.g. households compete for new housing as it becomes available, with effects on second-hand housing as “chains” of sellers and buyers form and complete), without any pre-defined order and without time being specifically divided into one-year steps;
- URBANLY is applying a partial market equilibrium process to adapt prices; this is updated as events occurred, and (unusually) will allow for future events to be input (by the model user) so that prices will be affected and affect other choices in anticipation of actual changes (such as transport infrastructure changes)
- significantly faster running to allow more time for model adjustment, testing and application.

E.5.3 Other comparable software packages may be available or under development.

E.5.4 Additional information on modelling in Japan was received too late to be fully integrated into this report. This advised that “One of the representative LUTI models in Japan is the HUMS model (Household Urban Micro-Simulation model)” developed by Professor Kazu Miyamoto and colleagues. “This model is an urban microsimulation model that uses only open data, and has been applied to case studies [of] in many Japanese cities such as Toyama, Sapporo, Sendai, and Toyohashi. In recent years, efforts have also been made to integrate activity-based transportation models. Major papers related to this model include [J1-J6 in the following table]. Furthermore, research is being conducted to extend the HUMS model as a social dynamics simulation using a multilayer network as shown in [J7-J9].”@@@

Table E-2 References for HUMS models

#	Reference
J1	Nao SUGIKI, Varameth VICHIENSAN, Noriko OTANI, Kazuaki MIYAMOTO: Agent-Based Household Micro- Datasets: An Estimation Method Composed of Generalized Attributes with Probabilistic Distributions from Sample Data and Available Control Totals by Attribute, *Asian*

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[135] Liming Wang, Paul Waddell (2013): *A Disaggregated Real Estate Demand Model with Price Formation for Integrated Land Use and Transportation Modeling*. Paper presented to the 92nd Annual Meeting of the Transportation Research Board, Washington DC

[136] email communication from Federico J. Fernandez, URBANLY, November 2023

#	Reference
	Transport Studies, Vol.2, No.1, pp.3-18, 2012.
J2	Atsushi SUGUKI, Nao SUGIKI, Kazuaki MIYAMOTO: *Development of Spatial Micro-Simulation for Forecasting Households Distribution*, Proceeding of the 15th CUPUM, 2017.
J3	Shogo NAGAO, Nao SUGIKI, Kojiro MATSUO: Development of Urban Micro-Simulation Model Using Open-Data, *International Symposium on City Planning and Environment Management in Asian Countries* Vo.12, pp.249-254, 2019.
J4	Nao SUGIKI, Shogo NAGAO, Batzaya MUNKHBAT, Atsushi SUZUKI, Kojiro MATSUO: Development of a household urban micro- simulation model (HUMS) using available open- data and urban policy evaluation, *Lecture Notes in Geoinformation and Cartography: Urban Informatics for Future Cities*, pp.343-370, 2021.
J5	Munkhbat BATZAYA, Nao SUGIKI, Atsushi SUZUKI, Kojiro MATSUO: Application and Result Comparison of Household Urban Micro-Simulation (HUMS) Model in Cities of Different Population Sizes, *The 14th International Conference of Eastern Asia Society for Transportation Studies*, Paper No.3225, 2021.
J6	Toko WADA, Nao SUGIKI, Mustafa MUTAHARI, Kojiro MATSUO: Evaluation of Location Optimization Plan Using Urban Microsimulation Model, *The 13th International Symposium on City Planning and Environment Management in Asian Countries*, Paper No.64, 2023.
J7	Nao SUGIKI, Shogo NAGAO, Fumitaka KURAUCHI, Mustafa MUTAHARI, Kojiro MATSUO: Social Dynamics Simulation Using a Multi-Layer Network, *Sustainability*, Vol.13, No.14, 13744, 2021. (https://www.mdpi.com/2071-1050/13/24/13744)
J8	Haruki NAKATANI, Nao SUGIKI, Fumitaka KURAUCHI, Mustafa MUTAHARI, Kojiro MATSUO: Future Policy Evaluation by Social Dynamics Simulation Using a Multi-Layer Network, *The 13th International Symposium on City Planning and Environment Management in Asian Countries*, Paper No.21, 2023.
J9	Mustafa MUTAHARI, Nao SUGIKI, Fumitaka KURAUCHI, Kojiro MATSUO: *Parameter Setting Examination of Social Dynamic Simulation Using a Multi-layer Network*, 12th World Conference on Transport Research, 2023. (Under the process of publishing as journal paper)

APPENDIX F GROUP 5: MARTIN CENTRE MODELS

F.1 History[137]

F.1.1 The origins of these models go back to the modelling work led by Marcial Echenique at the University of Cambridge Martin Centre (originally the Centre for Land Use and Built Form Studies) from the mid-1960s onwards, and its subsequent development in consultancy by Applied Research of Cambridge and then Marcial Echenique & Partners based in the UK, and by Modelistica based in Venezuela[138].

F.1.2 The original Martin Centre models were distinguished by a concern to represent the role of building stocks as an influence on human activities[139], in contrast with contemporary American models which assumed that people lived and worked directly on the surface of the land – or, in a more sophisticated interpretation, that housing, offices, factories etc could be perfectly and costlessly adapted to whatever distribution of residents and jobs arose from other factors.

F.1.3 The second characteristic of TRANUS and MEPLAN was the integration of an overall input-output or “economic base” framework, logit models of spatial choice for households and jobs conditional on where labour and goods/services were demanded, and a rent adjustment mechanism affecting both location choices and densities within floorspace.

F.1.4 The first model to combine these elements was developed for Bilbao (Basque Country)[140]. It was not at the time a named software package, but was used for a number of other applications and as the “MEP model” in the first phase of ISGLUTI[141]. It was developed into the first version of the MEPLAN package circa 1985; the very similar TRANUS package was in operation a little earlier.

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[137] Full disclosure: the author worked at ME&P from 1983 to 1990 and was Technical Director responsible for MEPLAN development from 1987 to 1990. In the 1990s he was also involved in some work using TRANUS and an early version of PECAS.

[138] For a more detailed history see Echenique, M H (1994): Urban and regional studies at the Martin Centre: its origins, its present, its future. *Environment and Planning B*, vol 21, pp 517-534. For a fairly representative selection of MEPLAN and TRANUS applications see the following six papers in that journal issue.

[139] Crowther, D and M Echenique (1972): Development of a model of urban spatial structure. In L Martin and L March (eds): *Urban Space and structures.* Cambridge University Press, London. (Based on a 1969 paper.)

[140] Geraldes, P, M H Echenique, I N Williams (1978): A spatial economic model for Bilbao. *Proceedings of the PRT Summer Annual Meeting,* PTRC, London.

[141] see Appendix J

F.1.5 ME&P was taken over by WSP in the 1990s, and support for MEPLAN ceased around 2010; the only remaining use of (part of) the software is in one of the DfT national models. TRANUS remains very much in active use and continues to be supplied and supported by its original developers, Modelistica[142]; versions are available for free download both as standalone software and as a plug-in to Q-GIS. One theme in TRANUS work has been to query the appropriateness of the assumptions underpinning the standard logit model, and to propose practical alternatives.

F.1.6 PECAS was developed by HBA Specto (Alberta, Canada) in the late 1990s and early 2000s, drawing on the ideas and experience of MEPLAN and TRANUS but seeking to address a number of theoretical shortcomings[143]. Its original development was substantially supported by the Oregon Department of Transportation's TLUMIP programme[144].

F.2 Description

F.2.1 A key characteristic of TRANUS and MEPLAN was the integration of three different and critical components:

- an overall input-output framework, used in different ways in different models (see below)*;*
- a set of spatial choice models, calculating where each zone's consumption of each commodity would be supplied, sensitive to the rents from the next component:
- the use of a rent adjustment mechanism, affecting both location choices and densities, to find an equilibrium in which all of households and jobs were located and all floorspace of each type in each zone was occupied; similar but slightly simpler models were applied for the "service" components of employment (i.e. not for the "economic base" employment).

F.2.2 The integration of the three main components was discussed at some length in a 1993 paper[145]. One important point to note is that in practice the input-output framework was used in one of two ways:

- in "urban" models, as an "economic base" mechanism, whereby "basic" employment "generated" households and households "generated" "service" employment[146] – but with the interactions directly between economic sectors (intermediate demands) **not** being modelled;

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[142] http://modelistica.com.mx/en/

[143] https://www.hbaspecto.com/products/pecas/pecas_history/

[144] Donnelly, R, W J Upton, B Knudson (2018): Oregon's Transportation and Land Use Model Integration Program: A retrospective. *Journal of Transport and Land Use* vol 11

[145] Hunt J D and Simmonds D C (1993). Theory and application of an integrated land-use and transport modelling framework. *Environment and Planning B* vol 20, pp 221-244.

[146] In some of the later MEPLAN models the proportion of employment treated as endogenous was very small – only local retailing and local (school) education.

- in “regional” models, where typically a more limited definition of the “economic base” was used, and the intermediate demands between sectors were important, with household demands being treated very simply or as fixed.

F.2.3 A further feature, regarded as central to the package designs at the time, was that matrices of transport demand were derived directly and very simply from the matrices of interaction in the land-use model: so the flows of labour from households (by residence) to jobs (by workplace) were converted directly into numbers of trips. The highly synthetic nature of the models, which meant that many variables were calculated from relatively few inputs, with some of the best-observed data (e.g. cordon counts) therefore emerging at the end of very long chains of calculation, was criticised by the present author in a 1994 paper[147].

F.2.4 Key features of PECAS (as for other complex package, not all of these used in every application) are

- in addition to distinguishing the zones where commodities, services or labour are produced and consumed, an additional concept of “exchange zones” where they are sold from producer to consumer, the main effect of which is to allow the model to distinguish flows where the producer pays the costs of transport from those where the consumer pays[148];
- at least some applications have considered intermediate demands (inter-industry relationships) and the demands generated via households in the same model
- a move from fixed input-output coefficients to variable relationships based on production functions;
- the option to use microsimulation to model processes of development and redevelopment at a parcel level, whilst retaining a aggregate treatment of building stocks by zone for the rest of the model[149].

F.2.5 The PECAS software is stated as being open source[150], though it is not clear that it has been used for new model development by anyone other than its authors.

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[147] Simmonds, D C (1994): The "Martin Centre Model" in practice: strengths and weaknesses. *Environment and Planning B* vol 21, 619-628. Paper presented to the Martin Centre 25th Anniversary Conference, Churchill College, Cambridge, October 1992.

[148] For example, a worker commuting to work incurs the money and time costs of commuting (the producer of labour is paying); a resident going shopping likewise incurs the money and time costs of the trip (the consumer is paying).

[149] See Wang, W, M Zhong, Y Zhang, Y Li, X Ma, J D Hunt and J E Abraham (2020): Testing microsimulation uncertainty of the parcel-based space development module of the Baltimore PECAS Demo Model. *Journal of Transport and Land Use* vol 13 pp 93–112

[150] https://www.hbaspecto.com/products/pecas/software/

F.3 Further documentation

Further documentation

F.3.1 The theoretical background and design of TRANUS are thoroughly covered in:

- de la Barra, T (1989): *Integrated land use and transport modelling.* Cambridge University Press, Cambridge.

F.3.2 PECAS applications:

- Fuenmayor, G J, J E Abraham, J D Hunt (2019): Building a PECAS Activity Allocation Module: the experience from Caracas. *Journal of Transport and Land Use* vol 12 pp 443–474.

APPENDIX G GROUP 6: MULTI-LEVEL DYNAMIC MODELS

G.1 TIGRIS

Documentation

Table G-1 TIGRIS documentation

Source: own literature search plus personal communication from Barry Zondag (Significance bv, Netherlands)

	Reference
T1	RAND Europe, BureauLouter, Spiekermann & Wegener (2003c): *Functioneel ontwerp prototype TIGRIS XL*. Report prepared for the Transportation Research Centre of the Netherlands Ministry of Transport, Public Works and Water Management [original model development report; not consulted]
T2	Barry Zondag (2007): *Joint modelling of land use, transport and economy.* PhD dissertation, Technical University Delft. TRAIL Thesis Series nr. T2007/4, The Netherlands TRAIL Research School, Delft.
T3	Barry Zondag, Michiel de Bok, Karst T. Geurs, Eric Molenwijk (2015): Accessibility modeling and evaluation: The TIGRIS XL land-use and transport interaction model for the Netherlands. *Computers, Environment and Urban Systems*, vol 49, pp115-125
T4	https://significance.nl/en/case/tigris-xl-land-use-transport-interaction-model/ (accessed 25 September 2023)
T5	Zondag, Barry and Karst T. Geurs (2011): Coupling a detailed land-use model and a land-use and transport interaction model. In E Koomen and J Borsboom-van Beurden (eds*): Land-use modelling in planning Practice*. Springer, Berlin.
T6	Barry Zondag, Michiel de Bok (2013): *The TIGRIS XL land use and transport interaction model for the Netherlands; applications and further developments*. Paper presented to ETC, 2013, available at https://aetransport.org/public/downloads/OJr2v/128-52414f382a8a5.pdf
T7	De Graaff, T and B Zondag (2013): A population-employment interaction model as labour module in TIGRIS XL. In F Pagliara, M de Bok, D Simmonds and A Wilson (eds): *Employment location in cities and regions: models and applications*. Springer, Berlin. (The core of this paper tests a possible enhancement of TIGRIS; it is not clear whether that was subsequently adopted as part of the ongoing system.)
T8	Schoemakers, A., & van der Hoorn, T. (2004): LUTI modelling in the Netherlands: experiences with TIGRIS and a framework for a new LUTI model. *European Journal of Transport and Infrastructure Research*, 4(3), 315-332. This paper described the original version of TIGRIS; it is mainly of interest in commenting on the reasons for that not being widely used, especially not in planning practice, and the way in which the development of TIGRIS XL was meant to respond to those issues.

G.1.1 The following description is based on [T2] except where otherwise indicated.

History

G.1.2 TIGRIS XL is a land-use and transport interaction model originally commissioned by the Transport Research Center (AVV) of the Dutch Ministry of Transport, Public Works and Water Management. It was designed and developed for AVV by a consortium of RAND Europe, BureauLouter, and Spiekermann & Wegener. Since 2011, the Netherlands Environmental Assessment Agency (PBL) has become a co-owner of the model and PBL uses the model for scenario and evaluation studies. Over the last 15 years the model has been continously improved and the version currently in use is TIGRIS XL version 7. Significance has carried out these developments commissioned by the Ministry of I&W and PBL [T4]. A recent review has concluded that it continues to represent broadly the state-of-the-art in LUTI modelling and should be maintained and further developed[151].

Description

G.1.3 "It is a design requirement that the key relationships, linking the transport and land-use system, are based on a formal statistical estimation. The relatively good spatial data conditions in the Netherlands make such a requirement realistic."

G.1.4 For the TIGRIS XL model a dynamic approach, focusing on the incremental changes, has been taken. Reasons for a dynamic incremental model are the need to explain time dependency of the changes. A dynamic model allows for the inclusion of time lags in the responses. This feature is important for the modeling of land-use changes resulting from transport measures, and is supported by empirical study.

G.1.5 Another reason for dynamic and incremental modeling is the small size of the annual changes in land-use; a large part of the land-use will be unchanged in a future period of for example 20 or 30 years. The small size of changes in land-use makes the spatial distribution at time t a good starting point to explain the land-use pattern at time $t+1$. An equilibrium model does not use the previous patterns as input and allocates all land-uses at a future point in time following market equilibrium conditions. Therefore an equilibrium model might easily overestimate these land-use dynamics: this often results in the use of high location specific impedances needed to represent the current pattern and correct the spatial dynamics. Location specific impedances represent the not explained part of the spatial distribution by the specification of the modeling. These impedances are usually derived in the base year to represent an observed distribution. A disadvantage of high location specific impedances is that these values are fixed (often to keep existing build up areas at their location) and do not respond to changes in the scenario settings or policies.

G.1.6 "The TIGRIS XL model is rather unique in its ambition to calculate the structuring impacts of inter-regional as well as intra-regional transport measures. This ambition is supported by a layered spatial structure, with a modeling of the changes at regional and local level."

G.1.7 **Demographic module**: Household formation, dissolution and transformation are not endogenously modelled. The complexity of underlying processes like marriage, living-together, divorce or separation, or death of a single household member and data restrictions on these processes prevent such an approach. Household transformations are derived from the outputs of a pre-existing model (PEARL, owned by the National Bureau of Statistics and Netherlands Environmental Assessment Agency) and applied to the data in TIGRIS at a zonal level; these zonal processes determine the overall demographic outcome.

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[151] https://www.pbl.nl/publicaties/naar-een-nieuw-tigris-xl

G.1.8 **Land and real estate market modules**: "The land and real estate market module processes the changes in land-use and buildings, office space and houses, and addresses both brown field and green field developments… The module distinguishes [between]

- the land market, including land regulation policies, and
- the real estate market addressing the development or restructuring of buildings."

G.1.9 **Accessibilities module**: the TIGRIS accessibility calculations start from logsum values calculated in the Dutch national transport model (LMS). As the LMS works directly with measures of utility rather than of generalised cost, these are supplied to TIGRIS as utilities: each value represents the expected utility of one tour, by a person of one type, from one zone to the destinations for one tour purpose[152], given the spatial distribution of those destinations and the characteristics of the transport systems that can be used to reach them. Weighted sums of these measures are then used to measure the expected utility of a household's daily trip making, the weights being the average daily number of tours of each type, by each person type, for each type of household.

G.1.10 Because LMS treats commuting trips as tours made by workers from home to work and back again, it does not directly produce output utilities that describe accessibility to labour from the firms' point of view i.e. how easily a given workplace can be reached by potential workers. A modified use of the worker's utility, called a "reflected logsum", is calculated to meet this requirement[153].

G.1.11 **Residential location choice**: "For all household types the travel time between current location and new location was a dominant variable. However, the distance decay functions for interregional migrations are less steep than for intraregional moves. The interregional moves are more likely to be initiated by a change of workplace, or education, and much less by housing and accessibility preferences."

G.1.12 A key difference from DELTA is that in TIGRIS XL the whole housing market is cleared within each time step (one year) by an iterative procedure which, for each of the six household types, adjusts the utility of locations with excess demand [until excess demand is removed]. This is in addition to the use of a price variable in the location choices, but it is argued that adjustment of the price variable would lead towards a mismatch in areas with large proportion of public housing [which is important in the Netherlands, and where market rents do not apply]. The long-term adjustments in TIGRIS XL are incorporated via the housing price variable, which adjusted so that the value at time $t+1$ is based on the market conditions, i.e. the housing demand/supply ratio, at time t. The housing price affects the residential

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[152] A tour is a round trip from home to a destination and back again, or – sometimes – a more complex chain of trips.

[153] The need to calculate accessibilities measuring "ease of being reached from origins" as well as "ease of reaching destinations" is common to all LUTI models where firms' choices are influenced by accessibility. A more common terminology is to identify "ease of reaching destinations" as "active accessibility" (measured for each origin), and "ease of being reached from origins" as "passive accessibility" (measured for each destination).

density of new construction sites and, depending on the assumption for the land market regulation, the number of houses to be constructed at a specific location. [T2]

G.1.13 In TIGRIS XL an iterative procedure is incorporated to match supply and demand in the housing market within a time period [T2]

G.1.14 **Employment location choice**: influenced by accessibility at municipality level, by a rule-based allocation below that. Like other models represents "firms" by jobs.

G.1.15 Solution: there is a simultaneous relationship between residential location choice (which is relocation [for existing households, presumably]) and employment location choice. "Jobs follow people" and "jobs follow jobs"; people follow jobs but mainly in inter-regional migration (see above); the relative importance of these two effects depends on the parameter values (see T2, p91).

Discussion

G.1.16 One feature of TIGRIS is that the residential location module works in terms of sample enumeration, and the output samples are used as inputs to the corresponding National Model System[154]. This avoids the need to run a population synthesizer as is required with purely aggregate land-use models[155]. This also means that the generalised costs (or more strictly, travel disutilities) passed back from the National Model System are correspondingly disaggregate and can reflect, for example, the influence of differences in household structure and car ownership in more detail than with a conventional aggregate transport model. However, this does not appear to prevent the TIGRIS design from being applied with aggregate transport models if the need arose.

Table G-2 Comparison of IRPUD, DELTA, TIGRIS and UrbanSim

Source: own analysis based on sources referenced in text

Aspect	IRPUD	DELTA	TIGRIS	UrbanSim
Zone system – land-use economy	Zones covering Dortmund city regionIn original design this was the middle level between a spatial economic model of the wider region and detailed models for parts of the city	Macrozones and zones (108 and 380 respectively in basic GB model; much more detail (up to 1000 additional zones in area of interest) in city-focussed applications	Municipalities and transport zones	Single, detailed level which can be zones, grid-cells or parcels
Interaction	Downward i.e. data	Two-way: data	Downward:data	None

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[154] In the original version, the sample was regenerated (by quadratic fitting) each year based on the relocations in the previous year and other (exogenous) changes (Zondag 2007 p104).

[155] For example, in the latest version of LonLUTI, where aggregate outputs from DELTA are used to generate inputs to the disaggregate MOTION transport model.

Aspect	IRPUD	DELTA	TIGRIS	UrbanSim
of levels	passed from region to city to finer model	passed from macrozones to zones and vice versa each year	passed from TIGRIS zones to transport zones	
Model operation	Monte Carlo microsimulation of household location, otherwise aggregate	Aggregate i.e. calculations are applied to groups of households, jobs etc	Disaggregate sample enumeration i.e. calculations are applied to a sample of households or of jobs, each case being weighted to indicate the number of households or jobs it represents	Microsimulation i.e. calculations are applied to each household, person, business and job in the modelled region
	Fixed sequences of modules	Fixed sequences of modules	Fixed sequences of modules	Fixed sequences of modules, but moving towards event-driven microsimulation?
Time step	Two years	One year (since prototype)	One year	One year
Transport model	Conventional model included in IRPUD	Simplified model included in DELTA, but usually used connected to a separate transport model	Used in conjunction with the Dutch National Model	Connected to separate transport models
Transport model zones	Identical to land-use model zones	Interface can convert DELTA outputs to different (usually finer) zone systems using a simple allocation procedure (equivalent to that in TIGRIS)	TIGRIS output is for transport model (LMS) zones	Parcel output can be aggregated to transport model zone system; grid cell output can be adapted. Zones should match.

G.1.17 All of the responses in TIGRIS are either simultaneous or backward-looking; there are no explicitly forward-looking effects.

G.1.18 Whilst TIGRIS itself works strictly with fixed scenarios at national level, it has been linked to a separate economic model which enables endogenous modelling of gross regional product, employment and income (see reference in Zondag, 2007, p91).

G.2 DELTA

Documentation

G.2.1 The following tables identify

- key papers on the DELTA design

- selected papers on DELTA applications in the UK.

Table G-3 Main references for DELTA design

Scope	Reference
Original design principles (details out of date)	Simmonds D C (1999): The design of the DELTA land-use modelling package. *Environment and Planning B: Planning and Design*, pp 665-684.
Residential location model – details	Simmonds, D C (2010): The DELTA residential location model. In F Pagliara, J Preston and D Simmonds (eds): *Residential location choice: models and applications*. Springer, Berlin.
Extension to multi-regional economic modelling	Simmonds, D C (2001): The objectives and design of a new land-use modelling package: DELTA. In G Clark and M Madden (eds): *Regional Science in Business.* Springer, Berlin, pp 159-188. Simmonds, D C and O Feldman (2013): Modelling the economic impacts of transport changes: experience and issues. In F Pagliara, M de Bok, D Simmonds and A Wilson (eds) (2013): *Employment location in cities and regions: models and applications*. Springer, Heidelberg.
Update including Highly Strategic Transport Model	Simmonds, D C (2019): Integrated modeling in the UK: practical usability of integrated models. *Journal of Transport and Land Use*, vol 12, pp 327-334.
Overview (to 2015, updated to 2017)	Simmonds, D C (forthcoming): The DELTA models and their applications. In Y Jin, M Batty, M Echenique and M Wegener (eds): *Applied Urban Modelling*. Oxford University Press for British Academy, in press[156].
Current status (typical application)	DSC (2022): *TELMoS18A Model Development Report*. Report to Transport Scotland, available at https://www.transport.gov.scot/media/51913/telmos18a-model-development-report.pdf

Table G-4 Selected references to DELTA applications: UK

Scope	Reference
Prototype	Simmonds D C and B G Still (1999). DELTA/START: adding land use analysis to integrated transport models. *Proceedings of the 8th World Conference on Transport Research,* Antwerp, July 1998, F1, 688.
Railways	Nicoll, J, Aramu, A and Simmonds, D C: *Land-Use/Transport Interaction Modelling of the Bathgate-Airdrie Railway Re-opening*. Paper presented to the European Transport Conference, 2006. Available at www.etcproceedings.org.
Roads	Simmonds, D C and O Feldman (2013): Modelling the economic impacts of transport changes: experience and issues. In F Pagliara, M de Bok, D Simmonds and A Wilson (eds) (2013): Employment location in cities and regions: models and applications. Springer, Heidelberg.
Congestion charging	Leitham, S, S Williamson and D C Simmonds (2005): *Assessing the land-use, transport and economic impacts of congestion charging in Edinburgh*. Paper presented to the European Transport Conference, 2005. Available at www.etcproceedings.org.

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[156] This remains the most recent academic paper focussed on the design of DELTA (and reporting the major developments from the 1999 *Environment and Planning* paper) but it was last revised in 2017; the book in which it is to appear seems to have been stuck in the publication process since then. Copies of the submitted paper are available from the author on request.

Scope	Reference
First application to Wider Economic Impacts	Feldman, O., Nicoll, J., Simmonds, D., Sinclair, C., Skinner, A (2008): Integrated transportation land use models for calculations of wider economic benefit in transport schemes. *Transportation Research Record*, No. 2076, 161-170
Local economic development initiatives	Simmonds, D C, S Dalgleish, N Byers (2014): *FLUTE: the application of a land-use/transport interaction model to prioritize city region investment*. Paper presented to the European Transport Conference. Available at www.etcproceedings.org.
Scenario modelling	Cann, R., Cragg, S., Nacar, V., Revill, E., Schnoebelen, C., Sibilla, C., Simmonds, D. (2021): *Modelling alternative scenarios for Scotland*. Presentation to European Transport Conference, 13-15 September 2021. Available at www.etcproceedings.org.
Impact of new vehicle technologies and transport business models	Sarri, P, I Kaparias, J Preston, D Simmonds (2023): Using Land Use and Transportation Interaction (LUTI) models to determine land use effects from new vehicle transportation technologies; a regional scale of analysis. *Transport Policy* vol 135, pp91–111.

G.2.2 See also the comparison with TIGRIS and UrbanSim in Table G-2 (page 139). The broader arguments for dynamic modelling, and the comparisons between DELTA, IRPUD and UrbanSim, are discussed in detail in a 2013 paper[157].

History

G.2.3 DELTA was developed by DSC in a collaboration with MVA and the ITS Leeds in response to a perceived demand for a full LUTI model, offering more functionality than the very limited static adjustment model DSCMOD previously developed by DSC with MVA[158]. It sought to integrate the property-market modelling of the Martin Centre tradition, then represented by TRANUS and MEPLAN (see Appendix F), with the dynamics and incremental structure exemplified in the IRPUD model (see section **Error! Reference source not found. Error! Reference source not found.**). The incremental structure meant that, like IRPUD and unlike the Martin Centre models, it took the base year situation as given (input data), and the dynamic form meant that it concentrated on forecasting change over time. This avoided the theoretical issues and practical complications of calibrating the model in the base year[159]. The design also avoided the need to split employment, and the processes of locating employment, into separate “basic” and “service” categories. However, it retained from the Martin Centre tradition an aggregate implementation (in contrast with IRPUD, which was partly a microsimulation model), and a focus on housing floorspace (rather than dwellings)

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[157] Simmonds D, Wegener M, Waddell P (2013): Beyond equilibrium: advances in urban modelling. *Environment and Planning B*, volume 40, pages 1051 – 1070.

[158] Roberts M. & Simmonds D.C. (1997). A strategic modelling approach for urban transport policy development. *Traffic Engineering and Control*, 38(7/8), 377-384. Paper originally presented to World Conference on Transport Research, Sydney, 1995.

[159] See discussion in Simmonds D.C. (1994). The "Martin Centre Model" in practice: strengths and weaknesses. *Environment and Planning B* vol 21, pp 619-628. Paper originally presented to the Martin Centre 25th Anniversary Conference, Churchill College, Cambridge, October 1992.

with households trading off between the floorspace they occupy, the cost (rent) of occupying it and the characteristics of its location (especially housing).

G.2.4 The original version of DELTA therefore drew mainly on theory from urban economics and urban dynamics, together with random utility modelling (used for all discrete choices).

G.2.5 There was also a specific aim to the original design of drawing on the wide range of empirical research in urban and property market economics, urban geography, etc, which had previously been very largely ignored in most urban modelling work. Like most other dynamic models, including IRPUD and UrbanSim (which was first developed at approximately the same time), it is modular in structure.

G.2.6 The Edinburgh prototype of DELTA had a single level zone system with relatively large zones (by transport modelling standards), and was linked to a correspondingly "strategic" transport model, START[160].

G.2.7 Major enhancements to the original design as summarised in Table G-5.

Table G-5 Major enhancements to the DELTA package

Source: from material at www.davidsimmonds.com (SYSTRA)

Feature	Year	Notes
Car-ownership	1998	Based on an incremental form of the national car-ownership model developed for the UK Department of Transport (subsequently modified in line with changes to the national car-ownership model)
Accessibility calculations within DELTA	1998	Previously calculated in the transport model to which DELTA was linked
Upper-level (macrozone): trade and production model, investment distribution model	1999	These components make up the DELTA Regional Economic Model (REM), and implemented a spatial input-output model (i.e. one in which the choice of where to purchase inputs is sensitive to trade and other costs) similar to that in regional applications of MEPLAN (and in an upper level of the IRPUD model), but with two-way interaction between the regional (macrozone) and local (zonal) levels.
Migration model (longer-distance moves between macrozones)	1999	Allow for longer-distance moves to be separated from local moves, with different propensities and different responses, with key variables being drawn from the zone-level housing and labour market models.

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[160] START was a later version of the model described in Bates J., Brewer M., Hanson P., McDonald D. & Simmonds D.C. (1991): *Building a strategic model for Edinburgh*. Proceedings of the PTRC Summer Annual Meeting, Seminar G, Brighton, pp 165-181. See also Roberts, M and D C Simmonds (1997), referenced above.

Feature	Year	Notes
Planning policy responses	2009	Allows the limits on development (representing planning policies) to be endogenously adjusted (subject to user-defined controls) to permit changes in floorspace beyond those envisaged in the exogenous planning inputs. This proved valuable as a way of allowing systematic changes in the amount of development permitted in cases where the exogenous inputs, obtained from local planning authorities, were highly restrictive in the longer term.
Variable productivity model (agglomeration and related effects in economic model)	2015	Incorporated agglomeration effects into the model, modifying GVA/worker and wages, and hence household incomes. Changes in total household income can be allowed to modify final demand (which will lead to multiplier effects including increased employment), or prevented from doing so (in order to maintain a given employment scenario)
Land Development Model	2015-16	Models development and redevelopment of floorspace on land, with endogenous choice of density levels and (if permitted) endogenous choice of floorspace type within the permitted range (e.g. whether office or industrial space is built on “employment land”). (Previously DELTA only considered floorspace, and the amount of development possible/permitted in each zone was defined in floorspace quantities.)
Highly Strategic Transport Model	2016	Provides for a simplified and very fast transport model, intended to be calibrated on results from a full and detailed transport model. This allowed a full LUTI model to be run wholly in DELTA software

Description (1): Accessibility calculations

G.2.8 The accessibility calculations are very similar to those in TIGRIS[161]. The generalised cost outputs from the transport model are used in combination with DELTA’s own land-use data to calculate a range of accessibility measures for each zone and macrozone. These are recalculated in each year; if the transport model is not run every year, the most recent available generalised costs are used with current land-use data.

G.2.9 The accessibility measures are calculated first as the expected generalised cost per trip of each type from each zone, given the available destinations and transport conditions. There are then weighted over trip purposes to obtain accessibilities by household type; for example, retired households are not directly affected by changes in accessibility to work, but may be affected by changes in accessibility to services. These accessibilities are conditional on car-ownership level; they are weighted by car-ownership when used in the location models. Accessibility to markets is also calculated for each industry sector, at macrozone level; changes in these accessibilities are used in investment location.

G.2.10 All of the other components of DELTA are to some extent sensitive to changes in accessibility over time, either directly or indirectly.

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[161] see Zondag and de Jong (2011): The development of the TIGRIS XL model: A bottom-up approach to transport, land-use and the economy. *Research in Transportation Economics* vol 31 pp 55-62.

Description (2): Economic and employment changes

G.2.11 Economic activity is measured in terms of employment, output and GVA. National (or model-total) growth in each of these variables is exogenously defined, and a base forecast is calibrated so as to reproduce that scenario under conditions corresponding to those in the exogenous forecast. Changes in the transport supply and/or changes in planning policy will then (to some extent) affect output and GVA; they may also be allowed to vary employment, or this response can be suppressed for consistency with Green Book default assumptions.

G.2.12 Economic and employment changes are brought about in four processes:

- the investment model, forecasting where industrial capacity will be increased or decreased, given changes in costs and changes in its accessibility to markets;
- the trade and production model, a spatial input-output model which forecasts
    - how much each sector will produce in each macrozone, and
    - the inputs that sector will purchase from other macrozones taking account of transport and other costs;
- the employment location model, which calculates the resulting changes in employment by sector and macrozone (normally based on production, but with exceptions for special sectors) and allocates them to the lower-level zones within each macrozone. This is strongly influenced by the availability of floorspace, and (usually less strongly) by changes in accessibility;
- the labour market model, which adjusts the choices of working-age adults about whether to work and where to work until all the jobs calculated in the employment location model are filled. (Note that this can only be run after household relocation has been modelled; the other changes can (in principle) be run in parallel.)

G.2.13 GVA per worker and wage per worker are also adjusted; incomes per household are adjusted both for changes in wages/worker and for changes in whether and where household members are working. Non-wage incomes are represented but are taken as fixed for each household type (i.e. they do not respond to changes in government revenue or to changes in total property rents in the way that they can do in urban SCGE models.)

G.2.14 Note that

- each choice is influenced by accessibility or transport cost terms, as well as by a range of other variables;
- different kinds of accessibility affect different economic sectors to different degrees, e.g. accessibility to domestic consumers is important for retail and some other service sectors, but not for manufacturing;
- the supply of floorspace is a particularly important influence on location at the local scale;

- competition for floorspace (or the lack of it) leads to immediate increases in rents, which affect both floorspace per worker and choice of zone – the model iterates to convergence on these effects, thus finding a short-term rent-based local equilibrium in each type of employment floorspace;
- as in RELU-TRAN, floorspace may be left vacant if demand is low (or falling rapidly); in other respects, each market must clear i.e. all employment must be located (subject to a minimum floorspace per worker), and the floorspace used must not exceed the existing stock of each type in each zone.

Description (3): Household changes

G.2.15 The demographic scenario is defined exogenously in terms of the numbers of households by type and the numbers of persons by broad age group (children, working-age adults, retired) in those households. The model is calibrated so as to implement these scenarios by applying a transition model to the households in each zone in each year. This, together with different rates of residential mobility for different household types, affects the number of households that may locate in each year. The majority of households do not even consider moving in any one year; this includes a very high proportion of older households, and a significant proportion of younger households. (This feature of DELTA contrasts with the endogenous model of whether-or-not-to-move in, for example, TIGRIS.)

G.2.16 The modelled processes affecting households are

- longer-distance moves (particularly influenced by employment prospects);
- local moves (particularly influenced by housing availability and (except for newly-formed households) by distance from previous location, but also affected by changes accessibility to work and services); and
- gaining or losing employment (see employment changes, above)
- increasing or decreasing car ownership.

G.2.17 Households making longer-distance moves are subtracted from the locating households at their origin and added to those at their destination. The local-level (re)location process is also the housing market model, i.e. rents adjust until markets are cleared (or housing is left vacant). The model uses Stone-Geary functions to forecast how households will divide their income between housing and other goods and services (“ogs”); this means that households consume a given minimum of housing and of ogs, then divide the balance of their income between these in a fixed proportion[162].

G.2.18 The changes over time in floorspace per household, and in consumption of other goods and services enter the measure of utility used in forecasting households’ choice of zone. The other variables included in the utility function are (typically)

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[162] This in itself is very similar to equivalent calculations in MEPLAN, TRANUS and PECAS; however, the use of the results from the household expenditure choice is quite different.

- changes in accessibility (by household type, as described above);
- changes in housing area quality (which can come about through development of new and (hopefully) better housing, through direct public intervention, or through households spending more on maintenance and improvements that benefit their neighbours); and
- changes in environmental quality. These could take many forms but are usually summarised in a measure of the volume of traffic in the zone, as a proxy for noise, pollution, severance, accident risk etc.

G.2.19 Note that the last two are “externalities” in that they are (almost) entirely the results of decisions by others, in contrast with the consumption of housing floorspace and of ogs, which are “internal” decisions of the household. Accessibility is a hybrid, in that transport supply by mode is affected by various factors but is outside the control of the individual household; but car ownership, which determines whether the household benefits from (usually much better) accessibility by car, is a household decision (strongly influenced by income, and assumed to be included within the expenditure on ogs).

G.2.20 Car ownership responds mainly to changes in income and in the number of workers per household; in current DELTA it is adjusted near the end of the sequence for each one-year period, after updating incomes for changes in employment.

Description (4): Development processes

G.2.21 Developer choices are represented by models of how much floorspace to build, and where to build it. Developers’ decisions are driven by expected profits, which in turn are driven by occupier demand: development therefore tends to follow businesses and households, whilst also being constrained by the inputs representing planning policy (which control the amount of building which can take place in any location at any time).

Description (4): Dynamics

G.2.22 DELTA is run in one-year periods. The transport model is usually run less frequently, for purely practical questions of run time. experience with the SITLUM model[163] suggested that running the transport model in alternative years is preferable if practical.

G.2.23 Most of the model works in terms of changes over time. The models of housing and employment floorspace involve iterative processes to clear each market in each period, but these act only on the minority of households and jobs that are being located in each period, and the variables calculated in those processes enter households’ and firms’ utilities of location in comparison with previous values. The length of time over which the changes in utility of location are considered is

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[163] Strathclyde Integrated Transport/Land-Use Model. See Aramu, A, A Ash, J Dunlop and D Simmonds (2006): SITLUM - the Strathclyde Integrated Transport/Land-Use Model. *Proceedings of the EWGT2006 Joint Conferences*, Politecnico di Bari.

the inverse of how frequently that type of household or jobs in that industry relocate, i.e. if households of a given type typically relocate once every seven years, those relocating will respond to changes that have occurred over the past seven years.

G.2.24 The development models generally assume that developers respond to recent conditions (particularly rents) in deciding where and how much to build, but that there is a timelag of several years before that development is completed.

G.2.25 The underlying principle is that the only instantaneous relationships should be those that are required for consistency. and that all the key models should forecast changes from the previous situation. The major exception to the latter is the trade and production model, i.e. the spatial input-output model, which forecasts the pattern of trade afresh in each period; it was so designed because at the detailed sub-regional level represented by DELTA macrozones there are rarely or never observed trade matrices to input to the base year.

G.2.26 All of the responses in DELTA are either simultaneous or backward-looking; there are no explicitly forward-looking effects.

Other related work

G.2.27 Two more major variants on the DELTA package were developed outside the core model described above. Both of these involved modelling housing supply in terms of numbers of dwellings rather than square metres of floorspace. One of these (known only as the "dwellings-based version of DELTA") was an aggregate model, like standard DELTA. It replaced the combined calculation of where to locate and how much space to occupy there with a more complex choice of zone, dwelling type and tenure, subject to a range of constraints. It also attempted to move to being a more strictly dynamic model by replacing iterative calculations finding market-clearing rents with an incremental adjustment of prices (for owner-occupiers) and rents (separately for private and social sectors) over time, with each one-year period being divided into smaller "time slices" (as in UDM). This was not particularly successful – the adjustment processes tended to leave too many vacant dwellings in some places/types/tenures and too many unhoused households; this was (as in some other models) resolved by a purely numerical reallocation, though this tended to obscure the intended responses to accessibility or other changes. Overall it was felt the fully-dynamic approach might be desirable in theory but was undesirable in practice, and subsequent applications (apart from SimDELTA, below) returned to the partial-equilibrium approach. (With hindsight, a partial equilibrium approach with multiples tenure might have been a good compromise[164].)

G.2.28 The other variant was SimDELTA (see references in **Error! Reference source not found.**, page **Error! Bookmark not defined.**), which also moved to modelling choice of zone, dwelling type and tenure, but in a microsimulation framework which draw on the IRPUD-MASTER tradition. Like IRPUD (and unlike, for

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[164] At least to distinguish social housing from the wholly-private sector. Whether privately-owned dwellings are sold or rented out can be difficult to forecast and quite volatile.

example, UrbanSim) microsimulation was only used for household modelling; like MASTER, it improved on IRPUD in that the individual households were modelled over time (in IRPUD, the microsimulation was a separate exercise in each one-year period). Again, the market-clearing rent adjustment was replaced by adjustments over time.

G.2.29 Both of these designs were completed to working prototype level, for London and the Greater South-East in the case of the dwelling-based model and for South and West Yorkshire in the case of SimDELTA. The general conclusions were

- from both studies, that disaggregating housing choice by tenure and dwelling type is more complex than one might expect – partly because the choices themselves are complex, but also because the supply is variable e.g. a dwelling that is offered for sale may be bought by an owner-occupier or by a buy-to-let landlord – or maybe offered for rent if no buyer is found;
- whilst it is obviously true that “the real world doesn’t iterate”, there are practical advantages in using some form of market-clearing mechanism – it is difficult to ensure consistent results otherwise;
- microsimulation is obviously attractive in that it gets away from the restrictions of having to group households into defined categories, but the resulting random variation in the model outputs is a major problem especially where the local results, as well as city- or region-wide results, are important.

G.2.30 Juhász and Koren developed a dynamic model of Budapest drawing on concepts from DELTA, TIGRIS and MARS, partly to demonstrate the feasibility of implementing and calibrating a “semi-sophisticated” model in a city with limited data availability[165]. Unfortunately they have not been able to pursue this further.

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[165] Juhász, M and C Koren (2017): Creating a two-way land-use and transport interaction model for Budapest. *Acta Technica Jaurinensis*, Vol. 10, No. 2, pp. 99-123. (20036)

APPENDIX H GROUP 7: URBAN SCGE MODELS

H.1 Introduction

8.1.1 The models considered in this Group are “urban” in the sense that they consider at least some spatial disaggregation within major cities. CGE models that treat the city region as a single unit, with spatial subdivision, are outside the scope of this review[166].

H.2 RELU-TRAN

Souces and documentation

H.2.1 The description below is based mainly on

- Anas, A, and L Liu (2007): A Regional Economy, Land Use, and Transportation Model (RELU-TRAN): Formulation, Algorithm Design, and Testing. *Journal of Regional Science* vol 43 no 3.

H.2.2 Other references consulted:

- Anas, A (2013): A summary of the applications to date of RELU-TRAN, a microeconomic urban computable general equilibrium model. *Environment and Planning B,* vol 40 pp 959-970. Note that this provides only the summary indicated in the title; it does not describe the model beyond listing the markets represented, but refers the reader to Anas and Liu paper (see above) for model description.
- Anas, A, and H Chang (2017): *How and how much do public transportation megaprojects induce urban agglomeration? The case of the Grand Paris Project*[167]. Department of Economic (State University of New York at Buffalo) and University of International Business and Economics (Beijing). This paper includes the equations of the model, which may be slightly different from the description above.

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[166] Examples include models of Paris (Hadj-Salem, H , A El-Mehdi, H Jayet, Q David, H Hammadou and M Kilani (2016) Using a CGE Model for analyzing the Macroeconomic impact of the Grand Paris Express project on the Ile-de-France Region. Paper presented to the 19th Annual Conference on Global Economic Analysis, Washington DC) and Glasgow (recent, apparently unpublished work by Fraser of Allander Institute).

[167] Note that the Grand Paris Express project has been considered in at least four LUTI models, as well as numerous other analyses. The economic issues and some (but not all) models are described in J-C Prager (ed): *Le Grand Paris Express: les enjeux économiques et urbains*. Economica, Paris.

H.2.3 The 2013 paper includes references to papers by Anas and co-authors on the use of the Chicago model to consider the impacts of cordon tolls and of changes in gasoline prices. These have not been consulted for the present review.

History

H.2.4 RELU-TRAN was developed by Professor Anas and colleagues, notably Dr Yu Liu, from 1998 onwards. It draws on urban micro-economic modelling research by Anas and others from the late 1970s onwards. For further detail see opening footnotes to each of the papers listed at H.2.1 and H.2.2.

H.2.5 The two applications identified are to Chicago and Paris. Details are for the Chicago application unless otherwise stated.

Description: overall

H.2.6 RELU-TRAN is “a dynamic general equilibrium model of a metropolitan economy and its land-uses” (A & Liu, 2007, abstract). Broadly speaking, it combines the microeconomic approaches to consumer and producer behaviour that are fairly standard in CGE models with random utility modelling of zone and other choices. It can be regarded as general in the sense that all of the goods, services and factors in the model have prices which affect the choices of those who (may) have to pay them, and nearly all of these prices are endogenously variable (the main exceptions being capital and imported goods). It is an equilibrium model in that the model is solved to find all those prices (and traffic congestion) and their consequences simultaneously; only floorspace supply is held fixed at each point of time, and allowed to change only over time through developers’ construction/demolition decisions.

H.2.7 That said, and without detracting from the achievement of building such a model, it should be kept in mind that it does not have all the features of a full CGE model. In particular, all of the money circulating in the economy is assumed to be spent on current consumption; there is no consideration of saving and investment, and no limit on the amount of capital available to firms. This is reasonable in the context of modelling one city in the USA economy (Chicago) or one city in the European economy (Paris), but would raise some questions if applied to a whole economy.

Population

H.2.8 The population is represented as a set of consumers who are also potential workers. There is an exogenous number of consumers in each skill group, thus defining the potential labour supply. Each consumer makes a joint decision of

- whether to work or not;
- if working, where to work;
- if working, how many hours per year to work at their workplace;
- where to live;
- what type of housing to occupy;
- how much floorspace of that housing type to occupy in the zone where they live;

- the value of retail goods and services they will purchase from each retail destination;

all subject to a budget constraint which depends on

- wage income, if the consumer is working (wage rate multiplied by number of hours)
- other income, consisting of
    - a share of total profits from rented floorspace
    - an exogenous element of "other income"
- less income and property tax

and subject to a time constraint, on the number of hours the worker-consumer can work. He or she is assumed to choose the utility-maximising combination on all seven dimensions of choice (noting that some are discrete and some are continuous) given

- the wages offered per hours at each workplace (for the worker's skill group);
- the rents demanded at each residence zone per m^2 of floorspace of each housing type;
- the prices of goods and services offered at each retail destination;
- the expected travel time and cost for each home-work and home-retail trip;

all of which are endogenous to the model, and where the first three (at least) are found in equilibrium with producers' and landlord's decisions (see below). (The full equilibrium model also finds the equilibrium between the land-use/economic system and the transport system and hence finds travel times and costs that are in equilibrium as well.) The model assumes that the "real" values to which consumers respond are distributed around modelled values so that the discrete choices are calculated by logit models.

H.2.9 Note that children and other dependents of consumer-workers seem to be omitted from the model. It is not clear how RELU-TRAN represents households with no potential workers (e.g. single retired people), who have incomes, occupy housing and consume goods and services, and who presumably cannot be omitted.

Producers

H.2.10 Each industry uses capital, labour, building space and intermediate inputs from other industries, and produces goods and/or services both for export (to outside the modelled region) and for internal (final or intermediate) consumption. Apart from floorspace, all inputs can be moved between zones and (presumably) imported from outside the modelled region. The supply of capital is perfectly elastic and equally available in all zones (p425).

H.2.11 Each industry operates with a Cobb-Douglas production function such that the overall mix of labour, space and the intermediate inputs is sensitive to the average price of each group; the mixes of labour skills, of building types (e.g. a sector requires a mix of office and industrial premises) and of intermediate inputs are all exogenous and fixed. These prices are determined by wages, rents, and the selling prices of inputs plus transport costs, all of which are found in the overall equilibrium solution. Each firm is assumed to minimise its costs. Firms make only normal profits, so prices are determined by costs.

H.2.12 In the Chicago application, the scale factor (or total factor productivity effect) in the production function is a fixed value by industry and zone.

H.2.13 The production function for each industry in each zone includes (like all such functions) a constant representing Total Factor Productivity which scales the product of the different terms (relating to capital, labour, space and intermediate inputs) into units of output. In the Chicago application of RELU-TRAN this is regarded as a constant that varies by industry and zone to account for place-specific productivity effects (pp426-427). In the Paris application, the initial values of this scalar vary by industry and zone, but also vary in forecasting; the changes are based on functions similar to those in TAG (and likewise based on Graham et al, 2009) (A&C p10).

H.2.14 There is a slightly different treatment of the construction and demolition industries, which sell to developers (see below) (p429)

Landlords

H.2.15 Landlords hold a fixed stock of floorspace of each type in each zone at any modelled point in time, and can only choose whether to let it at the prevailing rent or to keep it vacant. This choice is on comparison of the net income from letting (i.e. rent less the costs to the landlord if the space is occupied) versus the costs to the landlord if the space is vacant; the logit model is justified by the distribution of costs (but not rents) around the input values. (A&L 2007)|

Developers

H.2.16 The representation of developers' behaviour converts rents into prices and (I think) adjusts construction and demolition costs for current wage rates. There is an exogenous rent for vacant land (p429) and a fixed supply of land in each zone (p452).

H.2.17 "Developers buy vacant land (or a building) in the beginning of the period, then act as a landlord to operate the asset for rental during the period, and decide by the end of the period on whether and what kind of building to build (or whether to demolish an existing building) (p430). They therefore make decisions based on comparing (p430, equations)

- the value of keeping land vacant
- the value of developing land with a particular type of building
- the value of keeping existing buildings unchanged
- the value of demolishing existing buildings.

H.2.18 Random distributions of construction and demolition costs are assumed so that the choice between these courses of action is again a logit model (p431). A further condition is that investors in land and buildings[168] make only normal profits.

H.2.19 There is a one-period lag for development to be completed (p430). However, in the Paris model, it would appear that only one future year is modelled, and that the model runs to find a stationary equilibrium where "the stock of each type of building that is constructed must equal the stock of that building type that is demolished, and the land depleted by the construction of new buildings must equal the land created by the demolishing of existing buildings"

Government

H.2.20 The government sector is represented only by the input tax rates on income and and on property occupation. (A&L 2007 p 419)

Overall properties

H.2.21 The general equilibrium of the model satisfies five conditions:

- all consumers maximise utility, producers minimise costs and landlords and developers maximise profits, given all the prices and costs (endogenous and exogenous)
- producers earn zero economic profits, because they are competitive and operate under constant returns to scale: the price of output (at the factor gate or shop door) equals the cost of production (both average and marginal);
- real estate investors earn zero economic profits after competitive bidding for assets, receiving rents and capital gains, and paying costs and taxes;
- nonwage incomes are consistent with total building stocks and asset prices, plus other sources of income from outwith the region;
- all markets clear with zero excess demand (but note that residents can choose not to work, and landlords can choose not to let property).

H.2.22 The Paris model (A&C p37) adds an additional condition that "in each zone, the stock of each type of building that is constructed must equal the stock of that building type that is demolished, and the land depleted by the construction of new buildings must equal the land created by the demolishing of existing buildings". The non-wage condition is not mentioned in defining the general equiblrium but may still apply.

Transport

H.2.23 The TRANS part of RELU-TRAN is a transport model which is run to find an equilibrium with the RELU components. This is not reviewed here.

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[168] The relationship between "investors" and "developers" isn't quite clear on pp 431-432; they could be the same ac

H.2.24 Note that RELU-TRAN does not appear to consider car ownership in any way. This may be a reflection of its North American origins.

H.3 LUISA

Sources

H.3.1 The following description (for LUISA2.02) is taken from

- Ying Jin, Steve Denman and Li Wan (2019): *UK2070 Futures Modelling : Technical Report*. Report to UK2070 Commission by Martin Centre, University of Cambridge.

H.3.2 The use of LUISA2.02 for the UK2070 Commission is reported in

- City and Transport Research Group (2020): *UK2070 Futures Post-COVID Scenario Modelling: Main Report*. Report to UK2070 Commission by City and Transport Research Group, University of Cambridge.

H.3.3 Both are available at https://uk2070.org.uk/publications/

H.3.4 The LUISA2 model is also described in

- Martin Centre for Architectural and Urban Studies, Department of Architecture, University of Cambridge (2019): *Cambridgeshire and Peterborough Futures: Main Report*. Report for the Cambridgeshire and Peterborough Independent Economic Review

H.3.5 The mathematical description seems to be identical with that in the UK2070 work, though the implementation of the model involved more detail in the Cambridge/Peterborough region and more aggregation elsewhere.

H.3.6 Note also that the Martin Centre LUISA2 model should not be confused with the LUISA Territorial Modelling Platform developed at (or for) the European Joint Research Centre[169], which is used in conjunction with the Europe-wide SCGE model RHOMOLO[170]. LUISA forecasts changes in land-use, including the allocation of land-use to "societal" functions (including housing, but also leisure and recreation [and education, health service etc?]) and to "economic" functions (including employment), but does not in itself constitute a LUTI model.

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[169] https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-luisa/; https://joint-research-centre.ec.europa.eu/luisa_en

[170] For RHOMOLO see J Mercenier and others (2016): *RHOMOL v2 model description: a spatial computable general equilibrium for EU regions and sectors.* JRC Technical report JRC100011, European Commission. For an application of RHOMOLO to a major urban transport project, the Grand Paris Express, see Di Comite, F, G Mandras and S Sakkas (2019): L'impact du Grand Paris Express sur les territoires français et européens, in J-C Prager (ed): *Le Grand Paris Express: les enjeux économiques et urbains*. Economica, Paris. Interestingly, the impacts are forecast to be positive in all European regions, and the most positive impacts outside France are forecast to be in the Balkans.

History

H.3.7 LUISA was developed at the Martin Centre of the University of Cambridge Department of Architecture, and is therefore the latest in a line of models started in the 1960s. Earlier work on the LUISA2 design was carried out around 2009-11 and reported in 2013[171]; just to add confusion, at that time the name LUISA was applied to a different model in use at the Martin Centre[172]. LUISA 2 (which is considered) was developed subsequently and in use by 2019. Both versions apply to the whole of the UK, with the zones being local authorities (lower-tier, where a two-level system of local government exists).

H.3.8 The one fully reported application identified for this review was a study for the UK2070 Commission in 2019-20. That was a scenario testing exercises which sought to answer the following questions in relation to four alternative senarios:

- What would the effects be if the UK would face a prolonged period of low growth, if the trend distribution of business activities and sustained imbalance were to persist?
- To what extent would a geographically more convergent growth strategy help or hinder growth, productivity and quality of life?
- To what extent could the environmental capacities of the existing UK growth hotspots cope with the different distributions of jobs and housing?
- What roles could a geographically more convergent growth strategy play in fostering or hindering a green economic recovery stimulate local economies and embed upskilling at a regional level?
- Could a long-term strategy inform the design of short term, 'shovel ready' investments?

H.3.9 The four scenarios defined as the four possible combinations of

- two different scenarios for national economic growth:
    - a "low growth" scenario, which was regarded as "the lowest possible rates of population and productivity growth that could materialise"; or
    - "gradual recovery", with a gradual building up in rates of growth (which was considered more appropriate than a sudden post-pandemic return to relatively high growth rates;
- and two different scenarios for the regional distribution of growth
    - "business as usual" (i.e. continued divergence between prospering and left-behind areas, or

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[171] Jin, Y, M H Echenique and A Hargreaves (2013): A recursive spatial equilibrium model for planning large-scale urban change. *Environment & Planning B*, vol 40 pp 1027-1050.

[172] Echenique, M H, V Grinevich, A J Hargreaves and V Zachariadis (2013): LUISA: a land-use interaction with social accounting model; presentation and enhanced calibration method. *Environment & Planning B*, vol 40 pp 1003-1026.

- "slow levelling up".

H.3.10 The study did not formally appraise any particular interventions; its purpose was limited to assessing the impact that levelling up might have on the national and regional economies[173]. The main conclusions (p45) as that "a regional reconfiguration of jobs, housing and transport, making use of the essential endowment[s] and resources already present in the countries and regions, would not only increase average per person productivity, but also establish new engines of growth and prosperity outside London and the Wider South East.

H.3.11 LUISA has also been used to examine scenarios for the Greater Cambridge area; these have not been publicly reported in any detail. A description of the project is available online[174].

H.3.12 LUISA 2 includes its own transport model, but this was not used in either the Cambridge or the UK2070 work. It is understood that it has been used in more recent work.

Description

H.3.13 From the UK2070 Technical Appendix, p4:

"This model theory incorporates desirable features from

> (a) spatial computable general equilibrium modelling which provides a rigorous framework for predicting rents, wages and prices given system constraints, and
>
> (b) dynamic disequilibrium modelling which acknowledges the uncertain timing and indivisibility of many supply-side interventions and the unpredictability of many events in the wider economy."

"The recursive spatial equilibrium theory is encapsulated in a MATLAB based software app."

"The study uses data and insights from the past 50 years (from the mid-1960s) in the UK to calibrate the forecasting model for the coming 50 years (2021-2071). The prediction model mechanisms used are those which have been tried tested in past successful modelling projects (for a retrospective assessment of the performance of past modelling projects, see UK Research Excellence Framework, 2014; Echenique, forthcoming). In particular, the prediction performance of the core models developed for this study has passed our assessment using the more stringent, inter-temporal validation (for validation methodology, see Wan and Jin, 2017)."

H.3.14 When looked at in detail (see below) it is apparent that LUISA2 has many similarities to the RELU part of the RELU-TRAN model already considered[175] –

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[173] Note in passing that parallel work carried out for the UK2070 Commission using the DELTA package did appraise the benefits of a series of massive interventions aimed at bringing about certain elements of levelling up, though in the absence of cost data regarding those interventions, the project could not appraise their value for money.

[174] https://www.cam.ac.uk/economicbonfire#group-The-forecasters-Tb2Mv8zksk

including the same limitation of not modelling capital flows and investment, which is arguably a more serious omission in a national model. The key differences are that

- LUISA does not currently incorporate a floorspace supply model (partly because the equilibrium supply assumed in RELU-TRAN is not considered appropriate to the UK situation)
- LUISA does not incorporate a transport model comparable to the TRANS component of RELU-TRAN (or at least, it has not been used in applications to date).

H.3.15 Given the similarities to RELU-TRAN, the following paragraphs note only the differences.

Consumers

H.3.16 The model of consumers' behaviour is effectively the same as that in RELU-TRAN. (The published presentation is different, in that it separates out location choices from other choices/responses.) One refinement that does not seem to appear in RELU-TRAN is a non-linear transformation of commute travel times to better represent commuting behaviour[176], and another transformation of times to shops and services for similar reasons.

H.3.17 The more detailed treatment of transport costs, with car to distinguish money and non-money components,

H.3.18 As in RELU-TRAN, there are consumers who do not work; it is not clear whether not working is allowed as a choice, or affects a fixed proportion of the population defined as part of the modelled scenario. It is mentioned assumed that there is a time lag between a utility change and household relocation (p40 A1.4).

Producers

H.3.19 The model of producers' behaviour is also almost or exactly the same as that in RELU-TRAN as used in Paris, i.e. including an agglomeration effect on Total Factor Productivity by industry and zone, reflecting changes in the surrounding density of employment (p34, above eq 2).

H.3.20 LUISA2 does not model inter-industry linkages; it is not entirely clear whether RELU-TRAN does or not. In this respect, LUISA2 is similar to earlier Martin Centre models (see section F.2).

Landlords

H.3.21 It would appear that the modelling of floorspace use works on a simple market-clearing basis, with no provision for space to remain empty.

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[175] Similarities include using the same notation for many but not all variables. As a general comment, more agreement on notation between different modelling groups would be helpful to model comparison.

[176] This would seem equivalent to the cost-damping effect recommended in TAG.

H.4 Other LUTI-SCGE models

H.4.1 The RURBAN model was developed by Miyamoto (Miyamoto et al., 1986, Miyamoto and Kitazume, 1989, Miyamoto and Udomsri, 1996), based on both random utility theory and random bidding theory in its original formulation. Since the original formulation contained an inconsistency with the price mechanism in market equilibrium, Miyamoto et al. (2007) improved the model by redesigning the theoretical interpretation to solve the inconsistencies and incompleteness found in the model. The upgraded version of the RURBAN model was applied to a study of Sapporo, Japan, with a highly disaggregated zone system of as many as 8000 zones[177]. This tradition of modelling actively continues in Japan[178].

H.4.2 Other more or less comparable models outside the UK (not considered in detail) include TRESIS-SGEM, for Sydney (NSW)[179], though this appears to be a linkage of two models rather than a single system.

H.4.3 In addition, two SCGE-like variants on the DELTA package have been pursued in the UK.

H.4.4 The first, which was completed to a working prototype for Highways England, extended the present core package mainly by making prices for all goods and services explicit and variable, and replacing the input-output model with a system of production functions responding to those prices. In that respect it was very similar to the RELU part of RELU-TRAN, and to LUISA. However it differed in a number of key respects:

- the cost of labour in the production functions were time-lagged terms output from finding a separate, partial equilibrium in the labour market which (in the short-term) adjusted the numbers of people in work and their choice of workplace to satisfy the requirement for workers (so increasing wages resulting from a relative shortage of workers would over time tend to lead to a reduction in demand);
- rents in employment floorspace were treated in a similar way, i.e. the rents used in the production functions as the basic costs of space (by zone and type) were outputs from the previous year;
- in addition to the modelling of floorspace changes over time, there was an explicit model of investment/disinvestment in each area and sector, using

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[177] Description quoted from Jun M-J (): The effects of housing preference for an apartment on residential location choice in Seoul: A random bidding land use simulation approach. *Land Use Policy*, vol 35. https://www.sciencedirect.com/science/article/abs/pii/S0264837713001269

[178] References in English include [1] Shinichi Muto, Sudhan Khanal Madhu (2018): Integrated Model of CGE and CUE Modeling for Evaluation of Urban Transport Projects, Joint 10th International Conference on Soft Computing and Intelligent Systems (SCIS) and *19th International Symposium on Advanced Intelligent Systems (ISIS), pp. 19-26*; and [2] Tetsuji Sato, Kazuma Okada (2023): *A Quasi-Dynamic Location Equilibrium Model Considering Behaviors in Individual Unit for Policy Making Corresponding to Spread of Autonomous Cars.* 15th International Conference of Eastern Asia Society for Transportation Studies.

[179] D A Hensher, T Truong, C Mulley, R B. Ellison (2012): Assessing the wider economy impacts of transport infrastructure investment with an illustrative application to the North-West Rail Link project in Sydney, Australia. *Journal of Transport Geography*.

the available prices to enhance the simpler investment/disinvestment model in the standard DELTA package;

- the production functions and investment models operated at the upper (macrozone) level (approx. 80 macrozones in GB) rather than at the zonal (local authority) level (380 zones in GB). This maintained the DELTA characteristic of having distinct, though related, sub-models to calculate the levels of economic activity in each macrozone (typically representing a housing market and/or travel to work area) and the location of employment in the finer zone system below that level.

H.4.5 The second spin-off looked at the alternative approach of replacing the macrozone-level economic modelling components of DELTA with a fully-fledged SCGE model operating on the same macrozone spatial system. In pursuit of this, DSC developed an extension of their Strategic National Model with one extra macrozone for Northern Ireland, and KPMG LLP converted their CGE model of the UK economy into an SCGE model using the same spatial units[180]. The intention was that all of the components enhanced in the DELTA PFM (above) would be replaced by the KPMG SCGE. Two-way integration would ensure that the DELTA urban (zonal) model took account of economic changes coming from the SCGE, and that the SCGE would take account of migration and property market impacts coming from the urban model. Unfortunately, the integration of the two did not proceed any further, but work on the design did highlight a number of issues in linking the two models together and in their use of transport data. Chief of these was that SCGE models, if they consider transport costs explicitly at all[181], often consider only those costs which are identified in national accounts as purchase from the transport sector(s). Adaptation of the basic model is therefore required if the SCGE model (within a LUTI-SCGE framework, or on its own) is to consider the impacts of – for example – a high-speed rail scheme which would offer faster journeys at the same (or higher?) fares.

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[180] The KPMG SCGE model has been used for a variety of applications, including analysis of the welfare and GDP impacts arising from development that might be facilitated by East-West Rail.

[181] Many models have avoided the issues of transport costs altogether by using the “iceberg treatment”, which simply assumes that a proportion of each good or services “melts” (i.e. is lost to the consumer) for each kilometre it has to be transported. This is implausible but sufficient for macroeconomic models and very simple models with only one sector, but not in serious multi-sector SCGE models. See discussion in Koopmans, C and J Oosterhaven (2010): SCGE modelling in cost-benefit analysis: the Dutch experience. *Research in Transportation Economics* vol 31 pp 29-36

APPENDIX I LUTI MODEL PROGRAMMING

I.1 Issues

I.1.1 A specific question in the brief asked about the programming languages used in the models and packages considered. Available information is presented in the table below.

Table I-1 Programming languages

Note: this table only indicates the programming language of the core model calculations, where known. Most or all packages will have associated utilities implemented in other languages or packages.

Package/model	**Programmed in…**	**Source**
CubeLand		
DCM (Dynamic City Model)	Python ?	
DELTA	Fortran	Personal knowledge, confirmed by Tom Simpson (SYSTRA)
DELTA PFM	Fortran	
G-LUM		
ILUTE	XTMF	*https://uttri.utoronto.ca/files/2018/07/ILUTE-Integrated-Land-Use-Transportation-and-Environment-Model-Reboot.pdf*
ITLUP	Fortran ?	
LUISA	MatLab	UK2070 report
MARS		
MEPLAN	Fortran	Personal knowledge
METROPILUS		
PECAS		
PIRANDELLO		
QUANT	C#	
RELU-TRAN	Fortran	Anas and Liu (2007)
TELUM		
TIGRIS		
TRANUS	Fortran ?	
UDM	Vensim	Communication from Mike Costello (Steer)
UrbanSim	Python	Paul Waddell, personal communication

I.2 Computing precision

I.2.1 Without going into details, one significant aspect of model programming is the degree of precision in the input/output of data and in the calculations. Some packages work with single-precision arithmetic, which at best hold data to about 7 significant figures and are inevitably less accurate when considering the differences between forecasts of that precision. One rule of thumb in using such a model was that differences in individual results below 0.1% might be unreliable and differences below 0.01%; more aggregate results would tend to be more reliable. Increased attention to appraisal (and hence to detailed comparison between forecasts) has made this issue more important. Modelling the economic effects of transport change in something like an SCGE framework, where the impacts depend on very small changes in prices propagating through all the different parts of the economy, make the issue more important again.

I.3 Comments

I.3.1 A question was asked in discussion about preferred languages for LUTI modelling. Judging from present practice, the answers would seem to be

- for ease of software modification by users who are not specialist programmers: Python, because it is widely known and relatively friendly to non-specialists. Note however that ease of modification needs to be matched by strict version control to ensure that it is clear (not just to the model users at the time, but to other users of the outputs months or years later) how model runs have been defined.
- for speed in running core model calculations, especially where these are iterative: this is outside the present author’s expertise, though modern versions of Fortran (with optimising compilers) were considered competitive quite recently, and may still be. Models implemented in software dynamics package seem to run extremely fast but it is not clear what other restrictions these impose.

I.3.2 Note that once models move away from “instant calculation” then absolute speed is not the only criterion. This is especially true when model run times extend into hours and most running will be done overnight – at this point reliability in unattended operation becomes more important. (Note also the role of transport model run times in full LUTI operation.)

I.3.3 “Unattended operation” also leads to the argument that for replicability all model runs should record and be able to reuse all the inputs that affect the outputs. So arguably the ideal user interface for model use (as distinct from model development or calibration) is simply a “Start” button for the user to click, followed by information on progress (just for reassurance that something is happening) and – eventually - a message telling her that the model run is complete.

APPENDIX J ISGLUTI

J.1 ISGLUTI Phases 1 and 2

J.1.1 The International Study Group on Land-Use/Transport Interaction (ISGLUTI) was a major project coordinated (and in part financed) by TRRL (now TRL) during the 1980s and into the early 1990s. It involved most of the groups active in land-use/transport modelling during that period.

J.1.2 The first phase of ISGLUTI's work involved comparison of the models developed by the various groups, and comparison of the results obtained when a series of common scenarios or interventions was tested using those models – though these comparisons were complicated by the wide range of cities being modelled (from Tokyo to a small town in the Netherlands) and by difficulties in representing interventions consistently in very different models. The first phase was reported in a substantial book (see reference in table below).

J.1.3 The publication of the book ensured that the first phase of ISGLUTI attracted more attention than the second phase, which was published as a series of papers in *Transport Reviews*; subsequent papers by authors outside the group have often referred to the book as if it were the sole output of the study. The second phase was however more interesting in many respects, as it involved a number of attempts to apply some of the available model designs (and software) to some of the cities already represented by the original models. It was therefore possible to examine the results of testing a series of scenarios and interventions on different cities with one model, and of testing the same scenarios and interventions on one city with different models. The series of papers describing and discussing these results is listed below.

J.1.4 The study was significant within the UK in generating a cautious but continuing official interest in the potential of LUTI modelling to assist policy- and decision-making. Internationally, it created an informal network of modellers which was subsequently maintained by the World Conference on Transport Research Special Interest Group 1; most of those still active remain in contact today.

Table J-1 ISGLUTI references

Phase	References
1	Webster F V, Bly P H and Paulley N (1988) *Urban land-use and transport interaction: policies and models*. Avebury, Aldershot.
2	Webster F V, and Paulley N (1990) An international study on land-use and transport interaction. *Transport Reviews*, vol. 10, pp 287–308.
	Echenique M H, Flowerdew A D J, Hunt J D, Mayo T R, Skidmore I J and Simmonds D C (1990) The MEPLAN models of Bilbao, Leeds and Dortmund. *Transport Reviews*, vol. 10, pp 309–322.

Phase	References
	Mackett, R L (1990) The systematic application of the LILT model to Dortmund, Leeds and Tokyo. *Transport Reviews*, vol. 10, pp 321–338.
	Mackett, R L (1991) A model-based analysis of transport and land-use policies for Tokyo. *Transport Reviews*, vol. 11, pp 1–18.
	Wegener M, Mackett R L and Simmonds D C (1991) One city, three models: comparison of land-use/transport policy simulation models for Dortmund. *Transport Reviews*, vol. 11, pp 107–129.
	Mackett, R L (1991b) LILT and MEPLAN: a comparative analysis of land-use and transport policies for Leeds. *Transport Reviews*, vol. 11, pp 131–154.
	Paulley, N and F V Webster (1991): Overview of an international study to compare models and evaluate land-use and transport policies. *Transport Reviews*, vol. 11, pp 197–222.

[end]