A Review of the Literature
on the Application and Development of Land Use Models

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Introduction

This literature review is being conducted in the context of a research project in which the Atlanta Regional Commission (ARC) is exploring the possibility of enhancing the way it produces long range forecasts of land use, employment and population used as inputs in the travel demand modeling process. Therefore the focus of this review is on land use models with two important characteristics: (1) they either include a travel demand model as an integrated component, or are designed to interact with a separately developed travel demand model, and (2) they predict the geographical distribution of employment and households within a metropolitan region.

Approach to the literature

Since a separate task in ARC's research project is aimed at collecting evaluations from other planning agencies, this review instead focuses primarily on published works and the papers of model developers. The literature on land use models is vast, far more than could be covered in this project's time allotted for a literature review. Therefore, we focus attention on materials that will help ARC identify and begin to understand the candidates it should seriously consider in its search for improved models. Our search led to two excellent recent reviews:

Overview. Michael Wegener has led a long and distinguished career in this field at the University of Dortmund in Germany. While there, over the course of many years, he developed, enhanced and used an integrated land-use transport model of the Dortmund region. For the last two decades he has periodically issued an overview of the land-use transport models worldwide, with extensive bibliography including references to the other available reviews. His latest overview (Wegener, 2004) is the most up-to-date, comprehensive, authoritative and unbiased overview currently available, so it serves as our primary source of information for our overview of land-use transport models found in the overview section of this report. Because of its importance, a pre-publication draft of his overview is attached to our report. In our review, references and quotes of Wegener refer to Wegener (2004) unless otherwise noted. Wegener's review is supplemented with a recent paper by Harry Timmermans (2003), who reviewed the current state of land-use transport modeling in a keynote address at the 2003 International Conference on Travel Behavior Research. In our overview section, we list current land-use transport models, highlight important aspects that distinguish models from each other, and suggest a possible subset that may be most promising for ARC to consider for its own use.

Detailed comparison. Several papers have been written in recent years providing more detailed comparisons of subsets of the available land-use transport models. One of these reviews, by Hunt, Kriger and Miller (2005) is an updated version of a review (Miller, et al, 1998) that provided the main content for two other recent reviews (Dowling, et al, 2000; Waddell, et al, 2001). Not only is it the most widely quoted in-depth recent review, but it includes ARC's current ITLUP (DRAM/EMPAL) model and most of the models that are likely candidates for ARC's adoption. Therefore, a pre-publication draft of Hunt et al (2005) is also attached to this report, and serves as the primary source for our comparison section, in which we summarize the main features distinguishing the reviewed models. In our review, any references to or quotes from Hunt et al refer to Hunt et al (2005) unless otherwise noted.

Our literature review also included the retrieval and study of documents describing several of the models, and inquiries with model developers. Such information and references are scattered throughout this review paper. But before we embark on our overview and detailed comparison, we provide a brief and partial history of developments in the field of integrated land-use and transport models.

A Brief and Partial History

Wegener notes that Lowry's (1964) Model of Metropolis, a nested system of residential location and employment location models, was "the first attempt to implement the urban land-use transport feedback cycle in an operational model", and that it stimulated many more efforts by others to model the urban system. We note two important subsequent developments.

Putman developed and successfully marketed a Lowry-type model, ITLUP, also known by the names of its two main component models, DRAM and EMPAL (Putman, 1983, 1991, 1998). According to Hunt et al, ITLUP was calibrated for over 40 locations worldwide and as recently as 1997 there were still over 12 active applications in the United States alone.

The other important development was the emergence and pioneering work, over a period of many years, of the Martin Centre (Echenique and Owers, 1994). After many years of urban modeling at the Martin Centre, Marcial Echenique developed and marketed the model MEPLAN. Many modelers who have since devoted much of their careers to land use modeling spent formative years at the Martin Centre, including, among others, Tomas de la Barra, the developer of TRANUS (de la Barra et al, 1984), J Douglass Hunt, one of two primary developers of PECAS (Hunt and Abraham, 2005), and David Simmonds, the developer of Delta (Simmonds and Feldman, 2005). At the heart of most of the models emerging from the work of the Martin Centre and its brain trust is a spatial input-output model that uses production technology coefficients to link inputs with outputs for various industrial classes, and spatial choice models to distribute and link production and consumption geographically throughout a region. ITLUP, and the above-mentioned models developed by the Martin Centre cadre, represent the majority of the calibrated land-use transport models in use around the world today.

Meanwhile, apart from Putman and the Martin Centre group, significant sustained efforts in the field have occurred in various places around the world, usually in an academic setting under the leadership of one person, sometimes leading to a model that was implemented and used for an extended period of time in the university's region only. Primary examples of this kind of development include the IRPUD model of Michael Wegener, in Dortmund, Germany (Wegener, 1998), the MUSSA model of Francisco Martínez in Santiago, Chile (Martínez, 1996) and the METROSIM model of Alex Anas (Anas, 1994). These models have not, in general, been adopted in other locations, but under the watchful eye of their original developer, they seem to have flourished for many years.

This brief history, besides identifying several of the primary candidates for ARC's adoption, may provide a couple clues to the successful deployment of a land use model in a metropolitan region. In all the above examples, the successful implementations were implemented and supported heavily, over a period of many years, by the original developer's group. The experience of Putman and the Martin Centre models further suggests that a unifying modeling technique, known to work in practical application, and implemented in a software package, may be very important for taking a model that was successful in one location and implementing it successfully in other locations.

Timmermans (2003) argues that none of the developments since Lowry has really solved the basic problems that remained and were known after Lowry first developed the Model of Metropolis. According to him, the dream of effective land-use transport models has not yet become reality. Wegener himself acknowledges that, when it comes to the important task of calibrating the model, all existing models encounter difficulty. Our review of the literature identifies two other weaknesses that seem to be common to all of the reviewed models. First, they don't correctly deal with long-term dynamics. Either they rely on equilibrium assumptions despite the common understanding that urban systems exist in dynamic disequilibrium, or else they attempt to model dynamic disequilibrium without the data and scientific methods to statistically capture the phenomenon. In both cases, incorrect predictions are likely, in the former because statistically estimated models are based on the faulty equilibrium assumption, and in the latter because of the modeler's incorrect judgments about the nature of the disequilibrium. Second, they attempt to model extremely complex systems without methods that account for all the important phenomena displayed by the systems. The simplest models lack the power to capture phenomena of interest. For example, models without endogenous prices are unable to properly capture the interaction of price and demand for space. And the most complex models lack the data they need to statistically identify their parameters; they rely on the judgment and assumptions of a "master-modeler". For example, the master modeler of a sophisticated spatial input-output model might assume a particular set of production coefficients that is incorrect or becomes obsolete as technology changes. Although discouraging, perhaps these observations provide a helpful cautionary note. Any land-use transport model implemented by ARC will, at best, be an imperfect tool. It will be important to be aware of the model's limitations when it is first selected, subsequently when it is implemented, and ultimately when it is used.

In the face of these problems, the research community continues to seek better ways to model land-use and transport interactions. One of the popular avenues of development is the move toward disaggregate agent-based microsimulation (Miller et al, 2004). Motivated by the understanding that the aggregate behavior of urban systems, like that of the transportation subsystem, is the result of the behavior of many individual agents (developers, firms, households, workers, etc), these modelers attempt to explicitly represent the agents, simulating the individual behavior of each agent, and the interactions among them. A closely related research development is the attempt to integrate environmental modeling with land-use and transport models (Lautso et al, 2004). Some environmental phenomena of concern vary tremendously and continuously across space or are greatly affected by transportation phenomena that vary greatly across small increments of space and time. To a great extent, the research aimed at disaggregate integrated models of urban systems is fueled by advancing computer technology. But Wegener (2006) notes that none of the fully disaggregate agent-based modeling attempts has yet been successful, and expectations have been scaled back. Systems relying exclusively on disaggregate agent-based modeling technology are not ready for practical use in planning agencies, and may not be for a long time.

Overview

Wegener (2004) identifies 20 contemporary land-use transport models, and discusses their comprehensiveness, theoretical foundation, modeling techniques, dynamics, data requirements, calibration & validation, operationality and applicability. As listed by Wegener, they include (see Wegener for the bibliographic citations in this list):

BOYCE	the combined models of location and travel choice developed by Boyce (Boyce et al. 1983, 1985; Boyce and Mattsson, 1991; Boyce et al. 1992);
CUFM	the California Urban Futures Model developed at the University of California at Berkeley (Landis 1992, 1993, 1994; Landis and Zhang, 1998a, 1998b);
DELTA	the land-use/economic modelling package by Davids Simmonds Consultancy, Cambridge, UK (Simmonds and Still, 1998; Simmonds, 2001);
ILUTE	the Integrated Land Use, Transportation, Environment modelling system under development at several Canadian universities (Miller and Salvini, 2001);
IMREL	the Integrated Model of Residential and Employment Location developed at the Royal Institute of Technology, Stockholm by Anderstig and Mattsson (1991, 1998);
IRPUD	the model of the Dortmund region developed at the University of Dortmund (Wegener, 1982a, 1982b, 1985, 1986a; Wegener et al. 1991; Wegener, 1996, 1998b);
ITLUP	the Integrated Transportation and Land Use Package by Putman (1983, 1991,1998) consisting of the residential location model DRAM and the employment model EMPAL;
KIM	the non-linear urban equilibrium model developed at the University of Illinois at Urbana by Kim (1989) and Rho and Kim (1989);
LILT	the Leeds Integrated Land-Use/Transport model developed at the University of Leeds by Mackett (1983, 1990c, 1991a, 1991b);
MEPLAN	the integrated modelling package developed by Marcial Echenique & Partners (Echenique et al., 1969; Echenique and Williams, 1980; Echenique, 1985; Echenique et al., 1990; Hunt and Echenique, 1993; Hunt and Simmonds, 1993, Williams 1994; Hunt 1994);
METROSIM	the microeconomic land-use and transport model developed for the New York Metropolitan Area by Anas (1992, 1994, 1998)
MUSSA	the '5-Stage Land-Use Transport Model' developed for Santiago de Chile by Martinez (1991, 1992a,1992b; Martinez and Donoso, 1995; Martinez, 1996, 1997a, 1997b);
PECAS	the Production, Exchange and Consumption Allocation System developed at the University of Calgary (Parsons Brinckerhoff Ohio et al., 1999; Hunt and Abraham, 2003);
POLIS	the Projective Optimization Land Use Information System developed by Prastacos for the Association of Bay Area Governments (Prastacos, 1986; Caindec and Prastacos, 1995);
RURBAN	the Random-Utility URBAN model developed by Miyamoto (Miyamoto et al., 1986; Miyamoto and Kitazume, 1989; Miyamoto and Udomsri, 1996);
STASA	the master-equation based transport and urban/regional model developed for the metropolitan region of Stuttgart by Haag (1990);
TLUMIP	the land-use transport model of the US State of Oregon developed in the Oregon Transport and Land Use Model Integration Program (ODOT, 2002);

TRANUS	the transport and land-use model developed by de la Barra (de la Barra, 1982; de la Barra et al. 1984; de la Barra 1989, 1998);
TRESIS	the Transportation and Environment Strategy Impact Simulator developed at the University of Sydney by Hensher and Ton (2001);
URBANSIM	the microeconomic model of location choice of households and firms by Waddell (1998a, 1998b, 2002; Waddell et al., 1998).

Additional models, identified by Timmermans (2003) and the author, include:

ILUMASS	a microsimulation model developed by several universities in Germany (Strauch et al, 2005);
METROSCOPE	an integrated model system developed at Portland Metro (Conder, 2000);
RAMBLAS	a microsimulation model developed at the Technical University of Eindhoven (Veldhuisen et al, 2000);

Table 1 lists these 23 models and provides 14 columns of information about them. Each column identifies a potential model characteristic and, for each model, whether it has that characteristic. Three of the models, ILUTE, ILUMASS and RAMBLASS are academic research projects, either in progress or recently finished, which attempt to employ a microscopic agent-based modeling approach to all the major urban processes. Since these are far from ready for practical application, they are not analyzed further.

Each of the remaining 20 models is classified by columns 2-4 into one of three categories based on its overall theoretical architecture. KIM, Metrosim and MUSSA are strongly based on economic general equilibrium theory; they do not simulate the evolution of the urban space; rather, they predict an equilibrium state at a particular point in time. The state at any point in time is not time-path dependent. Each of the models in the second group (column 3) is strongly based on a unifying modeling method. The particular method varies across the models within the group, but they all are implemented with recursive simulations over time, and their predictions for a given time period depend on the conditions in prior time periods. Models in the third group (column 4) are also implemented with recursive simulations over time. Although their component models are integrated, they are more independently developed. The weaknesses of equilibrium models (column 2) and disequilibrium models (columns 3 and 4) have already been discussed above, and neither has been generally accepted as superior, although disequilibrium models have been more widely implemented and used. Among the disequilibrium models, unified and composite have both been successfully implemented. Again, neither approach has been generally accepted as superior.

Each of columns 5-8 identifies a model feature that several of the models share; some models have none of these features, and some models have as many as three of the four features. Fourteen models have endogenous real estate prices (column 5); twelve of these explicitly represent the market, with market clearing; the other two (IRPUD and UrbanSim) use delayed price adjustment. Although it is possible to model the distribution of employment and households without explicitly modeling real estate price mechanisms (e.g. ITLUP), this author recommends against it. Prices are a fundamental influence on behavior, and simultaneously depend on that behavior. Models should explicitly represent this interaction.

Six of the models use the economic input/output modeling method (column 6), with production technology coefficients determining the mix of inputs. The unified models in this group (MEPLAN, PECAS and TRANUS) use the I/O model as their unifying principle, including households, using elastic I/O coefficients and spatially disaggregating the formulation. Conceptually, this unifying feature is appealing. Also, among models with real estate price mechanisms, those that use the economic input/output method enjoy by far the most widespread usage. This author cannot rule out the possibility that a different approach could prove to be superior, but a model system with an economic input/output model at its core would clearly have a lower risk of failure or of falling into disuse.

Four of the models evolve their population over time (column 7), using hazard models of demographic change and household formation models. This is another conceptually appealing feature. However, the processes of demographic change and household formation are very complex, and it is likely that the current model implementations are simplistic, to the extent that they may not be superior to the methods used by the other models of predicting demographic change.

Seven of the models explicitly model goods transport (column 8), usually as part of the spatial economic I/O model. Given the importance of goods transport to the decisions of employers, and of its impact on the urban transportation system, it is conceptually attractive to include this aspect explicitly in the model.

All of the models use a transport model; some of them include it as part of the land use model, others require the use of an external transport model, and some of them can be used either way (columns 9 and 10). Since ARC uses a separate transport model, it will be important to choose a land use model that can interface with it, although it may be possible to use an embedded transport model for interaction with the land use model, and use the land use model's outputs only as inputs to the more detailed ARC transport model.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Microscopic agent based	Economic general equilibrium	unified with recursicve simulation	composite with recursive simulation	Endogenous real estate prices	Economic input/output	Demographic change and household formation	Goods transport	Includes travel model	Can interface with external travel model	Calibrated and in ongoing use	Actively used in multiple locations	Marketed actively	Available for consideration
BOYCE			+						+					
CUFM				+						+	?	?		
DELTA				+	+	+	+	+		+	+	+	+	+
ILUTE	+													
IMREL				+	+				+		?			
IRPUD				+	+		+		+		+			
ITLUP				+					+	+	+	+	+	+
KIM		+			+	+		+	+					
LILT				+			+		+		?			
MEPLAN			+		+	+		+	+	?	+	+	+	+
METROSIM		+			+				+	?	?			?
MUSSA		+			+					+	+		+	+
PECAS			+		+	+		+		+	?	?	+	+
POLIS				+						+	?			
RURBAN			+		+					+	?			
STASA			+					+	+		?			
TLUMIP				+	+	+		+	+	+				
TRANUS			+		+	+		+	+	?	+	+	+	+
TRESIS				+	+				+		+			
URBANSIM				+	+		+			+			+	+
ILUMASS	+													
METROSCOPE				+	+					+	+			+
RAMBLAS	+													

Table 1: Characteristics of 23 contemporary integrated land-use transport models

Columns 11 and 12 identify the extent to which models are actually being used today. Wegener's analysis is not complete in this regard. He writes that only few of the models are on their way to become standard software, and notes that ITLUP, TRANUS, MEPLAN and DELTA all have multiple applications (column 12). IRPUD, MUSSA, TRESIS and METROSCOPE, which were all developed for a particular metropolitan area, continue to be used in that area (column 11). It is not clear that any of the other models is actually calibrated and in use, although the author's information about these models is not complete. Some of the models appear to have either fallen out of use completely, or to have never been used in practice. Others, such as PECAS, are in the process of calibration in several locations, and others, such as UrbanSim, are in the process of calibration in at least one area after calibration attempts in other areas seem to have been abandoned. Before choosing to implement a model that has not been fully calibrated and placed in successful use in at least one location, it would be very important to understand why this is the case and assess the risk that the developer may not be able to successfully implement a satisfactory working model.

Column 13 identifies the models that are being actively marketed. For the most part, these are the ones that have multiple active implementations, but the list also includes models in active development. One model, METROSCOPE, is not being actively marketed, but has an active application and is being prepared for market in other locations (column 14). As with the list of active applications, the author's information may be incomplete. There may be additional models whose developers would say they are available for implementation in locations such as Atlanta, so it may be prudent to try to find them and inquire accordingly. However, it is very likely that any new implementation at ARC would come from the list of models in column 14; Table 2 provides contact information for them.

Model Descriptions

Hunt et al (2005, pp 331-336) provide a more detailed look at six of the nine models identified above as available for consideration by ARC. These descriptions are reproduced below (see Hunt et al for their bibliographic citations), followed by the author's similar brief descriptions of the other three models.

> **Integrated Transportation and Land Use Package (ITLUP)**. The ITLUP framework has been developed and applied by Professor Stephen Putman at the University of Pennsylvania, Philadelphia, USA, over 25 years. It includes a number of sub-models, the best known of which are DRAM (Disaggregate Residential Allocation Model) and EMPAL (Employment Allocation Model). It uses a Lowry-derivative form (Lowry, 1964) to allocate households (usually by four income categories, though further categorizations are possible), employment (usually by four types, though more detailed Standard Industrial Classification (SIC) groupings are possible) and travel patterns (public and private modes). Exogenous study area forecasts of employment, population and trips, activity rates and household types are inputs. Detailed documentation of the model is provided by Putman (1983, 1991, 1994), with useful summary descriptions also available (Webster *et al.*, 1988; Wegener, 1994; Southworth, 1995; Putman, 1996).
>
> Notable features of ITLUP are as follows:
>
> - ITLUP (more specifically, DRAM and EMPAL) is the most widely used spatial allocation framework in the USA today. A recent count indicates over a dozen active US applications (Putman, 1997), although over 40 calibrations have been performed across the USA and elsewhere.

- It contains a multinomial logit modal split sub-model, as well as a trip assignment sub-model that can support various network assignment algorithms. Trip generation and distribution are developed within DRAM, simultaneously with household location. However, DRAM and EMPAL often are used separately and have been linked in actual applications with other commercial travel demand forecasting models (including EMME/2, TRANPLAN and UTPS). Thus, considerable detailing of travel demand and travel costs can be provided through exogenous links.
- Compared with other frameworks, it has relatively parsimonious data requirements. Southworth (1995) notes that an important advantage of DRAM/EMPAL is its basis in generally available data (i.e. related to population, households and employment). However, it is also noted that this reflects a weakness of the approach; namely, that the framework does not account for land market clearing processes (or, it follows, other market clearing processes).
- A recent development is METROPILUS, which is aimed at improving linkages with geographic information system (GIS) databases and in revising the framework towards greater system modularity. It operates within an ArcView shell, which supports linkages with an ArcView GIS database, and is Windows compatible (Putman, 1997).

Model	Website or contact information
DELTA	David Simmonds Consultancy Suite 14 Millers Yard, Mill Lane, Cambridge, CB2 1RQ, ENGLAND t: +44(0)1223 316 098 dsc@davidsimmonds.com www.davidsimmonds.com
ITLUP	S.H. Putman Associates, Inc. Stephen Putman 215-848-2385
MEPLAN	Marcial Echenique & Partners Ltd. 49-51 High Street Trumpington Cambridge CB2 2HZ t: 01223 840704 admin@meap.co.uk
METROSIM	Alex Anas Professor, Department of Economics 405 Fronczak Hall, State University of New York at Buffalo, Amherst, NY 14260 USA Telephone: 716-645-2121 x-415 E-mail: alexanas@buffalo.edu
MUSSA	Laboratorio de Modelamiento del Transporte y Uso de Suelo Universidad de Chile, Blanco Encalada 1975 2º Piso, Santiago, Chile Fono/Fax: (56 2) 6971757, (56 2) 6996852 Email: info@mussa.cl www.mussa.cl
PECAS	John Douglas Hunt, Ph.D., P.Eng John E. Abraham, Ph.D., P.Eng http://hbaspecto.com
TRANUS	Modelestica Tomas de la Barra (58) 2761-5432 www.modelistica.com
URBANSIM	Professor Paul Waddell www.urbansim.org
METROSCOPE	Sonny Conder Portland Metro conders@metro.dst.or.us

Table 2: Contact information for the models available for consideration by ARC

MEPLAN. The MEPLAN framework is contained in proprietary software developed by Marcial Echenique and Partners Ltd in the UK, a private consulting firm. It draws on 25 years of experience in practical integrated urban modelling, with work on the software package itself beginning in 1985. It has been applied to over 25 regions throughout the world, including Sacramento, California and the Cross-Cascades Corridor in the US. Detailed documentation can be found in various sources (Echenique *et al.*, 1969, 1990; Echenique and Williams, 1980; Echenique, 1985; Hunt and Echenique, 1993; Hunt and Simmonds, 1993; Hunt, 1994).

MEPLAN is an aggregate model: space is divided into zones, quantities of households and economic activities (called 'factors' or 'sectors') are allocated to these zones, and flows of interactions among these factors in different zones give rise to flows of transport demand. The heart of the framework is a spatially disaggregated input–output matrix, or social accounting matrix, extended to include variable technical coefficients, labour sectors and space sectors. All economic activities, including households, are treated as producing and consuming activities, with consumption patterns expressed using technical coefficients. Spatial disaggregation is accomplished by having the further production arising to satisfy consumption allocated among the spatial zones according to discrete choice models reacting to the prices for such production. The resulting interactions among zones gives rise to the demand for travel.

Temporal change is simulated by considering sequential points in time. Space (both land and floor space) is 'non-transportable' and must be consumed in the zone where it is produced. The supply of space in each zone is fixed at a given point in time. The technical coefficients for the consumption of space are elastic with respect to price, and prices for space that ensure demand equates with supply in each zone are established endogenously as part of an equilibrium solution established for each point in time considered. Prices for the outputs of other sectors are established endogenously running back along the chains of production–consumption. Travel demands arising for a given point in time are allocated to a multimodal network using logit functions representing mode and route choice, taking account of congestion. Transport disutilities feed back into the next time period, representing lags in response to transport conditions. Exogenous demand, which is analogous to the 'Lowry' (1964) basic sector, provides the initial impetus for economic activity. Changes in study-wide exogenous demand and in the quantity of space in each zone from one time period to the next fuel economic change, with these changes allocated among zones.

Modelo de Uso de Suelo de SAntiago (MUSSA). MUSSA is an operational model of urban land and floor space markets developed by Professor Francisco Martínez for Santiago, Chile. It is 'fully connected' with a thorough four-stage model (known as ESTRAUS); together, the combined models are referred to as 5-LUT, and provide equilibrated forecasts of land use and travel demand for Santiago. The model has been used to examine various transportation and/or land-use policies, usually involving transit as a central component of the policy. Documentation of the model is provided by Martínez (1992a, b, 1996, 1997, 2000) and Martínez and Donoso (1995). Notable features of MUSSA include the following:

- Consistently based throughout on an extremely rigorous and compelling application of microeconomic theory.
- Equilibrium model of building stock supply and demand. Demand for building stock (whether by households or firms) is based on their willingness to pay (WP). Buyers attempt to maximize their surplus (WP less price actually paid), while sellers attempt to maximize the price paid. Building stock is supplied by developers so as to maximize profits, given the apparent demand. Building stock prices are endogenously determined within the equilibration process.
- Solves for a static equilibrium in the forecast year by adjusting the amount of building stock supplied, a supply response, and consumers' expectation levels (expected utility to be obtained from their housing), a demand response, until demand and supply balance. The model end state is path independent and does not require solution for intermediate year results, although such intermediate results can also be generated.

- Uses traffic analysis zones as its spatial unit of analysis, thereby providing a relatively fine level of spatial disaggregation. In addition, extensions to more micro-levels of spatial analysis are being investigated (Martínez, 1997).
- Highly disaggregated relative to most other currently operational models. The Santiago implementation has 65 household types and could be run using a large weighted sample of observed households (and their associated detailed attributes) in essentially a 'static microsimulation' format.
- Extensions are being investigated to incorporate zone-level environmental impact (emissions) calculations into the modelling system (O'Ryan *et al.*, 1996).

NYMTC-LUM. The NYMTC-LUM framework has been developed by Professor Alex Anas on behalf of New York Metropolitan Transit Commission (MTC), New York, USA (Anas, 1998). It is a simplified version of METROPOLIS, and the most recent of a series of land use and housing market models developed by Anas over the last two decades (Anas, 1982, 1992, 1994, 1995; Anas and Arnott, 1993, 1994; Anas and Brown, 1985). Notable features of NYMTC-LUM include the following:

- Consistently based throughout on microeconomic theory.
- Simultaneously models the interactions between residential housing, commercial floor space, labour and non-work travel markets, with explicit representations of demand and supply processes in each case.
- Housing prices, floor space rents and workers' wages are all endogenously determined within the model and are used to mediate between demand and supply processes within their relevant markets.
- Solves for a static equilibrium in the forecast year by finding the prices and wages that cause demand and supply in the markets being modelled to balance. The model end state is path independent and does not require solution for intermediate year results.
- Uses traffic analysis zones as its spatial unit of analysis (up to 3500 zones in the New York application), thereby providing a very fine level of spatial disaggregation relative to many other current models.
- In its current state of implementation, the model does not contain much disaggregation of its main behavioural units (households, employment, buildings).
- In its current implementation, the land-use component is not integrated with a travel demand model. Rather, it is 'connected' to the existing MTC travel demand model in terms of receiving as inputs model utilities from the MTC mode choice model. This is similar to the case for DRAM/EMPAL, MUSSA and UrbanSim.

Features of the model that facilitate its application by a transit property include: use of small traffic zones as the spatial unit of analysis; access to detailed transit network representations and mode choice models in the MTC travel demand model; and the microeconomic structure of the model that permits a range of economic evaluation measures to be computed (property values, consumers' surplus, producers' surplus, etc.). Earlier models have similarly been applied to the evaluation of the impacts of the proposed South Corridor rapid transit line in Chicago, Illinois (Anas and Duann, 1986), and the assessing the impacts of a range of road and transit service changes in New York (using NYSIM) (Anas, 1998).

TRANUS. The TRANUS package is proprietary software developed by Modelistica in Venezuela, a private firm run by Dr Tomas de la Barra. It draws on much the same modelling experience as MEPLAN, with the elements of the package first coming together in the early 1980s. A key feature of TRANUS is the use of a somewhat more restricted set of functional forms and modelling options within the framework allowing a more set approach to model development relative to MEPLAN. It has been applied to a number of regions in Central and South America, and in Europe. TRANUS models of the Sacramento and Baltimore, Maryland, USA, regions and Oregon have been completed or are under development. For detailed documentation, see De la Barra (1982, 1989), De la Barra et al. (1984) and Modelistica (1995).

UrbanSim. UrbanSim is an operational model of urban land and floor space markets developed by Professor Paul Waddell for Hawaii, Oregon and Utah, USA. A prototype has been completed in Eugene-Springfield, Oregon. The model is designed to work in conjunction with a traditional four-stage model in Eugene-Springfield, and is being connected to a new activity-based travel model in Honolulu, Hawaii. Although the initial development of the model was undertaken through the consulting firm of Urban Analytics, further development and support of the model is being done at the University of Washington. The model and software has been placed in the public domain by the Oregon Department of Transportation, and the University of Washington will support its release and dissemination through the Internet as part of an NCHRP Project 8-32(3), 'Integration of Landuse Planning and Multimodal Transportation Planning'. For documentation of the model, see Waddell (1998a–c) and Waddell et al. (1998). Access to documentation and to the model is available at www.urbansim.org.

Notable features of UrbanSim include the following:

- Uses a 'WP' framework similar in concept to that used in MUSSA, but differing in significant aspects such as in not assuming equilibrium.
- Disequilibrium model of building stock supply and demand with annual time increments. Demand for building stock (whether by households or firms) is based on their WP, or bid (observed prices paid rather than hypothetical WP, which is difficult to observe). Buyers attempt to maximize their surplus (WP less price paid), while sellers attempt to maximize the price paid. Building stock is supplied by developers so as to maximize profits, given the apparent demand. Building stock prices are determined within the market clearing process, which occurs at the submarket level of the traffic analysis zone and property type.
- Model operates as a dynamic disequilibrium in each year, with the supply component developing and redeveloping individual land parcels on the basis of expected profits (expected revenue less costs). Expected revenue is based on prices lagged by one year, and new construction choices are not assumed to be available for occupancy until the subsequent year. Demand is based on lagged prices and current supply, and prices are adjusted based on the balance of demand and supply in each submarket in each year. The model end state is path dependent and requires a solution for each intermediate year.
- Demand side of the model uses traffic analysis zones as its spatial unit of analysis (271 zones in the Eugene-Springfield application, 761 in Honolulu, over 1000 in Salt Lake City, Utah), thereby providing a very fine level of spatial disaggregation relative to many other current models. On the supply side, the model uses the individual land parcel as the unit of land development and redevelopment, making this the only model to date to use the parcel as the fundamental unit of analysis.
- Model is highly disaggregated relative to most other currently operational models. The Eugene-Springfield implementation has 111 household types and could be run using a large weighted sample of observed households (and their associated detailed attributes) in essentially a static microsimulation format.
- Model is based on the analysis of policy scenarios that include comprehensive land-use plans, growth management regulations such as urban growth boundaries, minimum and maximum densities, mixed-use development, redevelopment, environmental restrictions on development, and development pricing policies, as well as the range of transportation infrastructure and pricing policies handled by the linked travel demand models.

DELTA. The DELTA model is contained in a proprietary software package of David Simmonds Consultancy. Implementation of DELTA for a city or region requires licenses for software, maintenance and support, and is done under a consultancy contract. Development of DELTA began in 1995 with two key requirements: (1) it should be suitable for use as an add-on to an otherwise freestanding transport model, and (2) it should be constructed in terms of the processes of urban change. The first application was completed in 1996. Since then it has been implemented and used in several cities and regions in the United Kingdom.

DELTA runs in a recursive simulation, in conjunction with a transport model, representing urban change over time in a dynamic disequilibrium. DELTA consists of an aggregate zone-based urban component that is sometimes linked with a more aggregate regional model with larger geographic scope. The urban component has several linked submodels that predict (1) market-based time-lagged development of floor space (dynamic disequilibrium), (2) demographic change, (3) car ownership, (4a) location of mobile households (sensitive to space, accessibility, environmental quality, housing quality and utility of consumption), (4b) location of employment by type, (5) labor demand and supply, and (6) area quality. Within the regional model is (7) a migration submodel that predicts migration of households among the region's areas, (8a) an investment model that predicts industrial and commercial investment in response to improved accessibility, and (8b) a spatial input-output model to represent production and trade among the areas of the region. Documentation of the model is provided by Simmonds and Feldman (2005) and David Simmonds Consultancy (2004).

PECAS. The PECAS model was recently designed by Hunt and Abraham (2005), and is in various stages of implementation at several public agencies in the US and Canada. The software has been written in Java, and is available to other agencies. The PECAS developers view the PECAS framework as an evolutionary advancement and generalization of the framework used in MEPLAN and TRANUS.

At its heart, PECAS is an enhanced aggregate spatial input-output (or activity allocation) model. Production and consumption activities are defined, and each one is allocated via a three-level nested model, to activity locations (level one), technology options (level two—mix of commodities consumed and/or produced, given activity location) and exchange locations (level three—where the level two commodities are bought and/or sold). The activities include various industries and household types, and the commodities include goods, services, labor and floorspace. The model uses variable technical coefficients that are sensitive to resource costs and transport accessibility, and variable exchange prices that clear the market. PECAS also includes a space development module that stochastically simulates changes in state of development for every unit of space in the modeled region (in Sacramento the units are land parcels). The state change probabilities depend on real estate prices and development costs. The activity allocation and space development models run iteratively in yearly time increments along with a transport model. In each time period, the activity allocation model receives forecasts of aggregate economic conditions and allocates activities, achieving short term equilibrium. The transport model estimates the resulting travel conditions and the space development model predicts state transitions in response to the allocated activities. The results all provide input for the next year's iteration. Documentation of the model is provided by Hunt and Abraham (2005) and Abraham, Garry and Hunt (2005).

METROSCOPE. METROSCOPE is an integrated system of models developed, used and enhanced over time by Sonny Conder and colleagues at Portland Metro (Metro, 2001). METROSCOPE is not currently being marketed, but it is being prepared for market by Metro and PTV America, and will soon be tested in a neighboring region. METROSCOPE consists of residential and nonresidential real estate equilibrium models that develop land and spatially allocate employment and households on the developed land. The models include price setting mechanisms to clear the real estate markets, but rely on supply assumptions rather than a supply model, to determine the amount of land development. The models use regional employment and households as input from a regional economic model, and interact with a regional transportation model, so that inputs and outputs of the various model components are mutually consistent. The models run in 5-year steps and it is not clear whether the "consistency" referred to in the documentation represents an equilibrium condition in each model year, or whether the model outputs from one year serve as inputs for the next model year. The model system is integrated within a GIS-based data management system that maintains the spatial data at the parcel level, aggregates it as necessary for each of the component models, and de-aggregates all model results to the parcel level. Documentation of METROSCOPE is provided by Conder (2000), Metro (2001), Yee (1998).

Comparison

Using an extensive set of comparison tables, Hunt et al (2005) provide a more detailed look at six of the nine models identified above as available for consideration by ARC. Table 3 lists the tables and aspects of comparison included in their paper, which is attached for reference. The following text highlights some of the more notable aspects that distinguish the models; the author has not analyzed the other three models in the same level of detail as did Hunt et al, so they are excluded from this discussion. Italicized references to table numbers refers to the tables as found in Hunt et al.

Table 1 identifies some cautionary notes about the implementation status of the reviewed models. In contrast to the other five models, UrbanSim is new and unproven; although at least partially developed for several urban areas, it still lacks a calibrated version in use anywhere. The Anas model reviewed by Hunt is also new and unproven; furthermore it is a simplification of the MetroSim framework, lacking some of its intended functionality and integration. MUSSA has only been implemented in a Spanish language version in one city. The technical support group of MUSSA, MetroSim and UrbanSim are either very small or university based; the ability to support new implementations is not clear.

In *Table 2*, MEPLAN and TRANUS stand out in that their spatial I/O framework keeps them from disaggregating to very small zones; the data will not support accurate representation of the I/O flows at a fine zonal disaggregation. However, it should be noted that the accounting of these flows effectively integrates the model and provides theoretically appealing empirical constraints lacking in the other frameworks. UrbanSim stands out by its conceptually appealing use of dynamic disequilibrium in the modeled processes. However, it is not clear that the data and empirical estimation methods effectively achieve statistically sound and behaviorally rich dynamic disequilibrium in the model behavior.

Table 3 indicates that, although MEPLAN and TRANUS can be tied to an external travel demand model, they internally distribute trips, and do it with a very aggregate zonal structure compared to a standard travel demand model. The MUSSA travel demand model is very good, and fully equilibrated with the land use model component. The NYMTC MetroSim model may not be equilibrated with the travel demand model used to supply it with accessibility information. MEPLAN and TRANUS are the only models that explicitly model goods movement. However, they probably do an inadequate job of incorporating commercial flows into, out of and through the region.

Table in Hunt et al (2005)	Aspect of comparison
1 General facts (p 337)	developer
	operational history
	hardware and software platform
	commercial availability
	support
2 Treatment of time, land and space (pp 338-339)	time
	land
	space
3 Treatment of transportation networks and services (pp 341-342)	transportation networks
	transportation supply—transit representation
	transportation supply—goods movement
	transportation supply—other transportation services
4 Treatment of actors (pp 344-347)	persons
	households
	private establishments—general
	private establishments—developers
	private establishments—carriers
	public authorities
5 Motivational framework (pp 349-353)	housing market
	floor space market
	goods and services market
	job market
	personal transportation market
	goods movement market
	transportation infrastructure market
	car (vehicle) market
6 Spatial allocation processes (pp 354-357)	housing supply
	housing demand
	floor space supply
	floor space demand
	goods and services supply
	goods and services demand
	labour (workers) supply/demand
	demographic processes
7 Policy capabilities--pricing, infrastructure, services, regulatory, education and marketing (pp 360-362)	land use
	transportation
	other

Table 3: List of model aspects compared in Hunt et al (2005)

Tables 4 and *6b* indicate that all of the models may have difficulty accurately generating an accurate distribution of households by demographic categories that is desirable for the travel demand model. ITLUP requires an exogenously forecast regional total of households by income category; it is not clear how well it distributes other household attributes across the region's zones. In practice there is little or no endogenous segmentation of households by type in the MEPLAN and TRANUS models. Although MUSSA can work with a very detailed demographic representation of households, it requires exogenous forecasts of aggregate households by type, and it apparently does not distribute households by type according to a behavioral model. NY MetroSim does not appear to input or distribute households by demographic categories. UrbanSim's framework calls for demographic transition models, but it currently either relies on a population synthesizer for its population or it uses static transition probabilities. Because of the importance of this model characteristic's impact on the travel demand model, it should be studied carefully as models are further considered for implementation. Related to this, the interface between the land use model and the travel demand model should be carefully analyzed to understand whether and how ARC's recently implemented population synthesizer would work in the model system.

Table 5 identifies important differences in the handling of the housing market. ITLUP has no price mechanism at all. MEPLAN and TRANUS use an explicit 'within time step' market clearing equilibrium that fails to represent vacancies. MUSSA uses a theorietically sound and empirically rich equilibrium mechanism that also clears the market. NYMTC MetroSim uses a logit demand model of joint workplace and residential, a price sensitive supply model, and a market clearing equilibrium price. UrbanSim uses a price mechanism that is theoretically similar to the MUSSA approach, but without imposing an equilibrium solution. This is intuitively appealing, but it is not clear from the empirical results of the most recent model development (Waddell, 2004) that the empirical implementation correctly implements the theory or incorporates the necessary variables to make it properly sensitive to supply and demand.

Table 6a indicates that MEPLAN and TRANUS, unlike the other models, require exogenous forecasts of total floor space development and housing development in each period.

Table 8b indicates several differences among the models with respect to data requirements and implementation effort. However, the comparisons are not detailed enough to make the magnitude or nature of the differences very clear. The most obvious distinction is that UrbanSim requires parcel data.

We close the review by comparing the reviewed model systems on a few potential model selection criteria (Table 4). The list of criteria is not exhaustive. In addition to adding other criteria, ARC will need to decide their relative importance. The first four criteria are straightforward—a model system either satisfies the criterion or it doesn't—but the developers should be given the opportunity to dispute the author's evaluation. Some of the remaining criteria, although they may be very important, are not as well defined, and the author has been less able to evaluate them in the course of this review.

		DELTA	ITLUP	MEPLAN	METROSIM	MUSSA	PECAS	TRANUS	URBANSIM	METROSCOPE
1	In ongoing use in 2 or more locations. This demonstrates that the implementation is transferable.	+	+	+	-?	-	-	+	-	-
2	Calibrated and in ongoing use in at least one location. This demonstrates that the developer can actually make the chosen modeling approach work.	+	+	+	-?	+	-	+	-	+
3	Builds on an approach that the developer has implemented successfully. This applies to PECAS, which, although it is new, builds on the MEPLAN approach, which Hunt and Abraham have successfully implemented.						+			
4	Real estate demand and prices are endogenous. This seems to have become a standard in urban models. The effectiveness of the UrbanSim price mechanism is not clear.	+	-	+	+	+	+	+	+?	+
5	Interfaces effectively with an external travel demand model. The literature review does not conclusively answer the 'effectiveness' question, but it is clear that MEPLAN and TRANUS are 'packaged ' to work with an internal low fidelity travel demand model, which may make interfacing with an external travel model clumsy (see discussion in the text).	+?	+?	-?	+?	+?	+?	-?	+?	+?
6	Extent and detail of required exogenous forecasts of household demography, employment, etc. Better if the model generates the details internally, but it must do it well; if it requires detailed external inputs, then they must be generated somehow (see discussion in text).	-?	-	-	-?	-	-?	-	-?	-?
7	Geographic disaggregation of outputs, and disaggregation of households demographically, and of employment categorically, in categories most useful to the travel demand models (see discussion in text).	-?	-	-	-?	-?	-?	-	-?	-?
8	Data required for calibration. It is not very clear from the literature review how different the data requirements are among the models.	?	?	?	?	?	?	?	?	?
9	Ease and speed of operating the calibrated model	?	?	?	?	?	?	?	?	?
10	Ability to effectively use the new population synthesizer.	?	?	?	?	?	?	?	?	?
11	Ability to effectively interface with a new activity-based model.	?	?	?	?	?	?	?	?	?

Table 4: How the reviewed land use models compare on some potential model selection criteria.
(+ indicates criterion is satisfied; - indicates criterion is not well-satisfied; ? indicates uncertainty)

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