Integrated Land Use and Transportation Planning and Modelling: Addressing Challenges in Research and Practice

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Integrated Land Use and Transportation Planning and Modelling: Addressing Challenges in Research and Practice

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ABSTRACT *Academic research in integrated land use and transportation modelling is on the rise, in no small part due to growing interest from public agencies that need to improve their capacity to respond to complex policy questions arising in the context of transportation, land use and environmental planning. But the process of taking models developed in an academic research setting, where theoretical validity and the advancement of methodology receive high priority, and moving them into public agency settings in which priorities such as reliability, ease of use and staff capacity to explain to stakeholders what the models are doing, and why, create predictable gaps in understanding and can undermine a project. In this paper, we develop lessons from the experiences of multiple planning agencies in applying UrbanSim in their operational agency settings and integrating it with their transport model systems. In contexts as varied as Detroit, Honolulu, Houston, Phoenix, Seattle and San Francisco, we find that there are common elements to the tensions of appropriating a model system for their own use. We assess how the evolution in the design of the model system has responded to policy and technical challenges presented by this domain, and propose directions for further development.*

Introduction

Common sense and a good deal of research suggest that major changes in the transport system influence patterns of urban development and location choices of households and firms, and that major changes in land use patterns influence the number of trips, and their destinations and modes. In short, land use and transportation systems are closely intertwined, and models used to support transportation planning need to be integrated with land use models to capture these effects (see e.g. Cambridge Systematics *et al.*, 1991; Paulley and Webster, 1991; Southworth, 1995; Garret and Wachs, 1996; Parsons Brinckerhoff Quade and Douglas, 1998; Miller *et al.*, 1999; Environmental Protection

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Agency, 2000; Wegener, 2004; Dowling *et al.*, 2005; Waddell *et al.*, 2007). Though there are still sceptics about the degree of influence of transport projects on urban development, the emergence of transit-oriented development as a subfield in research and practice attests to the growing significance of the integration of land use and transportation at even very localized scales. At the other end of the scale spectrum, the interdependence of land use and transportation have increasingly been recognized in federal legislation such as US federal transportation acts TEA-21 (1998) and SAFETEA-LU (2005). In 2010, the Obama administration announced its partnership for sustainable communities that links for the first time the activities of the Department of Transportation, the Environmental Protection Agency and the Department of Housing and Urban Development in promoting more sustainable communities across the programmatic domains of transportation, housing, economic development and the environment.

The land use–transportation nexus also includes air quality, as recognized in the Clean Air Act and its amendments (1990), and exemplified by the Portland LUTRAQ process (Cambridge Systematics *et al.*, 1991), and a series of lawsuits beginning in the Bay Area (Garret and Wachs, 1996). More recently, the State of California has adopted Assembly Bill 32 (2006), which aims to reduce greenhouse gas (GHG) emissions by 80% of the 1990 levels by the year 2050, and Senate Bill 375 (2008), which provides more direct action to curb urban sprawl and the emissions it produces by additional auto-oriented travel. SB 375 even goes so far as to require that metropolitan planning agencies (MPAs) within the state directly address these objectives by developing advanced activity-based travel models and land use models. This is by far the most prescriptive legislation to date, advancing the mandate for integrated planning of land use, transportation and GHG emissions.

Given the preponderance of research evidence, and the increasing use of that research to bolster legal requirements to integrate the planning of land use, transport and air emissions, one might conclude that we have crossed the Rubicon on this topic. Unfortunately, the task of implementing integrated land use, transportation and emissions planning within operational planning agency settings still faces formidable challenges. Metropolitan planning organizations (MPOs) in the US context are responsible for developing regional transportation plans (RTPs), and are the institutional focal point for much of the legal activity that is pushing for more integration of these three dimensions. In this paper, we explore some of the key challenges faced by MPOs in following through the implementation of integrated planning, and how one particular modelling platform, UrbanSim, is evolving to help MPOs and the diverse stakeholders in this process to meet these challenges.

The paper is organized as follows. In the next section, we develop generalizations of the challenges confronted in integrating land use and transportation planning, which provide a context within which integrated models are developed, and to which they must respond. The subsequent section takes up the challenges to integrated modelling, many of which are technical challenges, but some of which address more direct aspects of the planning challenges, including aspects of usability, responsiveness and transparency. The third section then describes how design choices for the UrbanSim model system and the Open Platform for Urban Simulation (OPUS) were shaped by these challenges. The paper concludes with an assessment and consideration of future directions.

Challenges for Integrated Planning

There are many reasons that integrated land use and transportation planning has not proceeded as fast or as far as some would have expected, not the least of which are that the domain is intensely controversial, it involves many institutional and non-institutional stakeholders with divergent values and mandates, and the sheer complexity of the issues and interdependencies is high. Add to this, the threat of legal action for failing to comply with the prescriptions of legislation such as the Clean Air Act Amendments (see e.g. Garret and Wachs, 1996) or the new California legislation (AB32 and SB 375) and one begins to wonder how progress has been made at all in this domain. Challenges to integrated planning of land use, transportation and emissions arise from at least the following sources.

Conflicting Institutions

Different institutions have responsibility for different aspects of the domain: transportation investments are coordinated by MPOs, but cities, counties, the state and even private institutions in the case of privatized toll facilities, and a myriad of public transit agencies all have mandates and control different aspects of the transport system. Land use plans are controlled by cities and within unincorporated areas by counties, as delegated by individual states. Air quality is controlled by a state air quality board. Other infrastructure investments that interact with transport, such as water and sewer, are generally controlled and managed by special purpose districts, though they can in some cases be controlled by local jurisdictions. From even this abbreviated description, it is abundantly clear that there is an inherent problem that arises from many institutions having narrow and often competing mandates. Coming to agreement on objectives for integrated planning, or even on the need to coordinate plans, is a tough sell to these institutions. Policies that might be optimal for a metropolitan region, arising from close coordination among these infrastructure and land policies, will be all but guaranteed to be suboptimal for each institution individually, given their narrower scope and constituency. In this regard, it is tantamount to asking institutions to act in ways that are not consistent with their mandates and the interests of their immediate stakeholders. This is a fundamental conflict, and until there is a broader framework that subjects all of these institutions to pressure to align their interests with broader metropolitan objectives, it is not likely that implementing integrated planning will advance far, no matter what tools are used.

Conflicting Values

Values differ among both institutional and non-institutional stakeholders, including the citizens of a metropolitan region, and all manner of advocates for specific objectives ranging from environmental protection to limiting the scope of government, pose fundamental challenges that no technical process will resolve magically. Most metropolitan areas operate within a very imperfect democracy, and governance structures to manage the political process in a democratic way for metropolitan regions are rare indeed. Democratic processes are institutionalized at city, county (to a lesser extent), state and federal levels, leaving metropolitan areas generally with no governance structure for democratic decision-making. MPOs, or the earlier Council of Government structures in the US context, have little authority and no directly elected boards to oversee their actions, and, with very few exceptions (e.g. Portland, Oregon and Minneapolis, St. Paul, Minnesota), have no direct service delivery responsibility and no direct tax revenue to use for services. In short, metropolitan governance has little leverage in the USA. This means that the political will to develop aggressive management and integration of planning objectives must come from the state or federal level, along with means to revise the governance structure to delegate these responsibilities to a metropolitan level. California may be a test case in moving in this direction, though the process is very early in its implementation at this time. The absence of metropolitan governance structures may pose both a challenge and an opportunity; however, as we explore later in this paper, within this vacuum there may be opportunities for experimentation, particularly in the use of social interaction technologies over the web, to facilitate democratic discourse and planning.

Conflicting Epistemologies

Divergent epistemologies surely also factor into the assessment of the problems of integrating planning. Some individuals, groups and institutions are most comfortable using Delphi or other more informal forms of soliciting information and consensus from stakeholders. Others are more comfortable using quantitative methods and models, and feel that this is required to provide a common artefact that can distil common ground into a coherent and systematic representation. These differences are related to the gap between *implicit knowledge* and *explicit knowledge* addressed by Te Brömmelstroet and Bertolini (2010). In practice, these differences have led to some bifurcation of planning practices into what may be called visioning and sketch-planning, that rely more on participants knowledge and assumptions, on one hand, and on integrated models that rely more on scientific knowledge and empirical testing, on the other. Often these divergent approaches will lead to different conclusions about the problem or the solution, as is to be expected from quite different approaches. The real issue may be less whether qualitative or quantitative epistemologies are more or less correct, than whether some combination of them provides sufficient behavioural and empirical validity to become useful as an artefact for facilitating democratic deliberation in a contested domain.

Conflicting Policies

Conflicting policies at the federal level and below do not make the integration of land use and transportation planning any easier. Though federal legislation such as TEA-21 and the CAAA indicate that there is a need to assess the impacts of transport infrastructure on land use patterns and subsequent induced travel demand and air emissions, there are other requirements that are in direct conflict. For example, the alternatives analysis for highway projects that seek federal funding are required to hold land use fixed across the alternatives for a specific highway corridor, directly denying any possible impact of the alternative corridor transportation infrastructure on land use. Presumably this restriction is imposed to reduce the burden of monitoring whether local planning agencies are 'cooking the books' to shift land uses in ways that would be more supportive of the need for the transport project they desire to implement. But clearly this contradicts other federal policy and undermines the capacity of local and metropolitan activity to promote integrated land use and transportation planning. A similar scenario applies to transit planning, where the Federal Transit Administration imposes extremely restrictive rules on how the analysis of alternatives in a transit corridor are to be evaluated—and again undermining the ability to adapt land use to support the proposed transit alternatives. Surely we will need to find ways to open up the planning process on the project evaluation level to be consistent with broader federal guidance on integrating planning efforts.

In the next section, we turn attention to the use of integrated models and to the challenges therein. We draw on extensive experience in the development and application of one particular platform, UrbanSim, for this assessment.

Challenges for Integrated Modelling

Transportation models have been used for evaluating alternative transportation plans for many decades, in spite of their well-known limitations (see e.g. Beimborn *et al.*, 1996). Integrated land use and transport models are more recent in their emergence, but their development and use have been riddled with challenges. Lee (1973) wrote a scathing critique of the early efforts to develop large-scale integrated urban models developed up to the early 1970s. The criticisms outlined 'seven deadly sins' of urban models, and largely focused on problems encountered in the models of the late 1960s and early 1970s, including what Lee saw as excessive complexity, excessive data requirements (for the time), and design flaws that he characterized as wrongheaded and overly mechanical. Lee's critique has been widely cited as contributing to a decline in activity on integrated models in the 1970s and 1980s. During this period, only two integrated modelling frameworks are found much applicable in practice: the spatial interaction model system DRAM/EMPAL (Putman, 1983), and the spatial input–output model systems TRANUS (de la Barra, 1995) and MEPLAN (Echenique *et al.*, 1990). At a conference sponsored by the Travel Model Improvement Program of the Federal Highway Administration in 1995, drawing together practitioners, academics and consultants involved in the development and use of integrated models, a consensus emerged that many of the problems identified by (Lee, 1973) and updated in (Lee, 1994) still described the state of affairs in 1995. The challenge was to develop new approaches and tools that would overcome these critiques and find more widespread adoption and use.

In the years following the 1995 TMIP conference, there has been a resurgence in interest in integrated modelling in the USA, bolstered by the mandate of the ISTEA and CAAA legislation that emphasized the need to coordinate land use, transportation and air quality planning. In short, there was a compelling need for integrated models, an emerging consensus on how to approach the science of developing such models, and a new mandate to pursue their development and adoption. The key challenges still facing integrated modelling and their application in practice include the following.

Transparency

Models will not have credibility as tools for decision support in complex, conflict-laden domains such as land use, transportation and environmental planning, unless they can be explained with a sufficient degree of transparency. The term 'Black Box' has been used to criticize precisely the lack of transparency in earlier models (Beimborn *et al.*, 1996). This is not to say that models cannot be sophisticated, or must be trivialized to a very low common denominator that virtually anyone can understand because it is overly simplified. Albert Einstein has been often cited as stating that theory should be as simple as possible, and no simpler. This principle has been called Einstein's Razor, in reference to Occam's Razor, which can lead to oversimplification. In the context of integrated modelling, there are many emerging sketch planning tools that provide simplicity and transparency, but little in the way of validity in representing how the world works. In this sense, there is a conflict between the principle of transparency and that of validity.

Behavioural Validity

For a model to be credible for use in a contested domain, it must have sufficient *behavioural validity* to be believable as an independent artefact, within some clearly defined scope of applicability. Behavioural validity is a somewhat broader term than theoretical validity, which would be a more purely academic term, and includes more common sense or intuitive understandings of how the world works. There may be conflicts between theoretical validity as assessed by different academic disciplines, for example between economics and sociology or psychology or political science, which use different theoretical frameworks to explain observed phenomena. Further, there may be conflict between local knowledge or intuition of residents or other stakeholders, and theoretical or empirical research. But the most compelling, credible and behavioural theories will tend to be confirmed across multiple dimensions of disciplinary research and local knowledge. Models that lack any form of behavioural and theoretical foundations can not pass the credibility test, and are not ultimately useful in supporting integrated land use and transportation planning. To make this case clearer, suppose one convenes a set of stakeholders who have only a superficial understanding of the way the real estate market works, and solicit from them a 'model' of a local real estate market, and 'predictions' about the future based on some proposed intervention. It is possible that the reasoning and predictions of such an exercise will be valid, but the odds are low that it would be able to withstand critical scrutiny. This criticism applies also to planning tools that do not have a theoretical or behavioural basis, and which are now increasingly being used to facilitate visioning or sketch planning workshops.

Empirical Validity

Models must be tested against observed data in order to assess their empirical validity. That is, no matter how much or little behavioural validity a model might have, it is not useful unless it can respond to input assumptions and make predictions that reasonably well correspond to observed reality. This is the process that some refer to as *model validation*. While there are many alternative means of undertaking such an exercise, it should be clear that if a model is intended to be used to predict outcomes well into the future, it should be able to capture the essential trends in outcomes over some period of history. Many models do not go through any form of validation, and leave it to the user to simply believe the outputs. This is a dangerous activity, in that many users of such models place undue confidence in the results, simply because they are produced by a model and perhaps by an academic. Such faith may be ill-founded where models have not been adequately validated against observed data, over time. Further, the models must be able to withstand scrutiny from the perspective of being free from bias. If they are perceived as having significant biases in their empirical validation, especially over time, they lose credibility.

Ease of Use

Beyond the behavioural and empirical validity conditions outlined above, if a model is inscrutable and too complex to explain, it also will ultimately not succeed in practice. If it requires the developer to provide extensive and ongoing support, with no assimilation of capacity to use and modify the model system by its users, it will be far less compelling than a model that accomplishes this aim. In short, a model system must strive to achieve a threshold of usability that makes it possible for staff within planning agencies to become capable users. The easier the better, since complexity invites errors. But this priority obviously must be traded-off against behavioural and empirical validity. One could make a stunningly easy-to-use model with absolutely no behavioural or empirical validity. In fact, there are many such tools now available.

Computational Performance

If we find a model system that meets the above criteria, we are doing well. But it is possible that such a model will have such poor computational performance that it is rendered irrelevant for most applications. Current generation travel models are veering close to and often over this threshold, with run times for a single year in some cases longer than a full day to simulate a day of travel. Less than real-time simulation is not an improvement over simply observing cities! On the other hand, approaches that emphasize interactive speed for use in stakeholder meetings and other similar workshop settings are often of the sketch planning type with no behavioural or empirical validity. They are fast, but at the cost of realism.

Flexibility

It is a truism to admit that we do not yet have in hand the ultimate models that will satisfy users in all cases and for all their desired applications. We continue to see improvement in theory, in empirical methods, in software development techniques, in user interface techniques, in data and so forth. As these continue to change, they alter the scope of what is feasible, and what is the best available option to develop and use a model to support decision-making. As a result, models and software platforms that are too rigid become a serious constraint, and limit applicability. Different users will have different data and needs, and it is clear that models need to be adaptable to these conditions if they are to be widely used.

Data Availability and Quality

In practice, probably the most daunting problem in implementing a model is developing the input data for it. In some cases, the data requirements are intimidating to even the most intrepid users. But the real concern is that the science and tools to develop data that is usable in modelling are far from addressing the needs of users. Input data such as parcels, employment records, building and price data are notoriously incomplete and error prone. Further, it is quite difficult to integrate them into a coherent database that is internally consistent. A rough approximation is that 75% of the effort and an even higher percentage of the time involved in developing model applications is due to the difficulty of developing the data for the model system. This is a very important obstacle, and must be addressed.

Uncertainty

Uncertainty is a topic that has only recently come into the lexicon of integrated modelling, but is increasingly important in making risk assessments of alternative policy choices or infrastructure investments. Take as an example the assessment of one project, the potential replacement of the Alaskan Way Viaduct in Seattle, Washington. It has been damaged by an earthquake and the risks are high that the elevated waterfront freeway will collapse in the next earthquake. The risk of catastrophic failure is a very tangible one, and the timing of this is inherently uncertain. Further, the alternatives that have been considered to date, ranging from retro-fitting the existing facility, to digging a tunnel to replace it, to using a lower capacity surface boulevard with transit as a less auto-oriented option, all face uncertainty in terms of their costs and benefits. The public is rarely provided information on these aspects of uncertainty, though they are surely germane in choosing among risky alternatives. Much remains to be done before models are up to the task of addressing this problem of uncertainty in a principled way.

UrbanSim

UrbanSim is one of the projects that emerged since the mid-1990s with a specific focus on addressing the challenges facing integrated land use and transportation modelling (Waddell, 2000, 2002). It was designed and continues to evolve to address the challenges to implementing operational integrated models, and to at least be cognizant of the difficulties for integrated planning, which are often political, institutional and philosophical in nature. In this section, we revisit the challenges laid out in the preceding sections of the paper, and examine how these have shaped responses in the design and implementation of UrbanSim.

Institutional and political context has shaped the design of UrbanSim in several direct ways. Recognizing that land use, transportation and environmental (air, water) planning are carried out by different institutions and that the domain is very diverse in terms of stakeholder values and institutional mandates, UrbanSim was designed to be an experimental laboratory for analysis of policies, and to allow those policies to be disaggregated to reflect the local distribution of policy mandates. Priority was given in the design to the intended use as a scenario evaluation system, with substantial flexibility to express different policy inputs such as land use regulations and development subsidies or costs, in addition to roadway and transit system levels of service and their connection to parcel, neighbourhood and regional land use patterns. Figure 1 captures the essential elements of the design. It represents the background of institutions and competing stakeholder values as a political context in which land use, transportation and environmental policy choices are made. Various processes may be used in different locations to arrive at some articulation of overarching public policy goals and objectives.

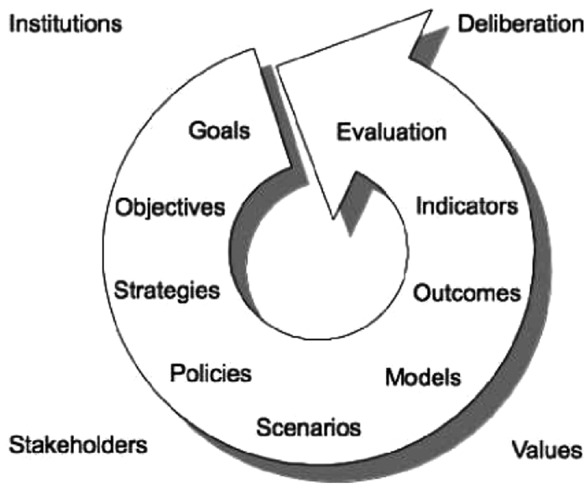

Figure 1. Integrating models in the political and planning process.

Regional visioning exercises such as Envision Utah or the Urban Land Institute Reality Check process are used in numerous regions as a means of bringing together a set of stakeholders to attempt to achieve some consensus about the vision for the long-term future of the region. Unfortunately, these exercises often confound ends and means, and go well beyond setting overarching goals and objectives, but lack the tools to undertake a systematic assessment of alternative policies to achieve them.

An alternative approach would integrate modelling into a participatory decision-making process, by making it easy for diverse stakeholders, possibly assisted by workshops such as has been done in regional and community visioning exercises, to move through an iterative process, beginning with an articulation of goals and objectives, and then moving systematically into an assessment of the policy tools available to governments (infrastructure, land regulations, taxes, fees and other incentives), and how these tools might be configured to collectively achieve the desired outcomes. Once these policy tools are assembled into policy *scenarios,* they could be used as inputs into an integrated model system to produce predictions of outcomes. From the outcomes, evaluation indicators may be computed and visualized, in order to make an assessment of the degree to which the policy scenario has accomplished the desired goals and objectives. Iterative experimentation is anticipated in order to explore the design space and come to an enriched understanding of the trade-offs involved. In this design, the models need to be credible enough to be used by parties that have often very conflicting preferences. It has to be credible and useful. We turn next to the more tangible implementation choices needed to accomplish this.

Transparency and behavioural validity are closely related objectives for integrated modelling, and the interaction between these two objectives points towards a design for models that closely reflect behaviour that is observed in daily life. It has led in the case of UrbanSim to adopt a micro-simulation strategy that directly represents agents and the choices they make in a way that is behaviourally natural and intuitive, and that can at the same time be readily understood, at a general level, by non-technical stakeholders (e.g. general citizens). The UrbanSim design has attempted to capture the essential set of agents and their behaviours and to

Table 1. Agents, choices and models in UrbanSim

Agent	Choice	Model
Household	In- and out-migration	Demographic transition model
Household	Residential moves	Household relocation model
Household	Residential location	Household location choice model
Person	Work at home	Work at home model
Person	Job choice	Workplace choice model
Business	Birth and death	Economic transition model
Business	Business relocation	Business relocation model
Business	Business location	Business location choice model
Developer	Parcel development	Real estate development model
Market	Real estate prices	Real estate price model

use these to create models that directly represent them. Table 1 depicts the mapping between the key real-world entities and choices and the models used to represent them. Two agents warrant further comment. Developers are real-world agents, but there is relatively little data about them in terms of their identity, size and internal financial data. Developers are still represented in UrbanSim as abstract agents, since they help to explain the supply side of the real estate market and data do exist on when and where different kinds of developer actions occur by observing development activity. Last, the role of prices in the real estate market is a complex one. In the table the agent is identified as the market, but this is an abstract agent, and in reality, prices arise from a complex set of interactions among consumers, suppliers and financial entities and institutions. Prices are currently modelled through a reduced form called hedonic regression, that reduces complexity while making reasonable predictions of prices. In recent research, development of auction type models to predict location choice and prices simultaneously is being explored.

There are active (and endless) debates among academics about whether prices fully clear the market or whether we ever observe markets in equilibrium in reality. These are points that begin to widen the gap between practitioners and academic modellers. In UrbanSim, the design has been influenced by the observed differences in the timing of what consumers can choose (relocating to another dwelling) versus the longer time frame required for suppliers of real estate to respond, often over multiple years for larger-scale projects. This timing differential gives rise to dynamics of housing booms and busts (witness the current housing bubble as a case in point), and is the epitome of disequilibrium. UrbanSim has thus far been used to model consumers as acting within the short-term time frame of less than one year, facing fixed housing supply. Developers have been assumed to respond to short-term changes and to make longer-term commitments to developing real estate, which can phase over multiple years. Other variants on these interactions and dynamics are being actively explored in further research, with the intention of continuing to refine the behavioural realism of the model system, and at the same time retain a high degree of transparency that makes it readily understandable.

Users need models that provide a reasonable representation of accumulated theoretical understanding of the economic behaviour of agents (e.g. generally choosing the less expensive option, quality and all else being equal), but the particular algorithm used to ‘clear the market’ is not likely to be chosen on purely theoretical grounds. Models must also pass the empirical validity test, to which we turn in the next section.

A final aspect of transparency is software licensing. Model users are increasingly expecting to be able to examine the source code implementing a model system, and to make changes in it if necessary. The UrbanSim software developers have adopted an open-source licensing for the UrbanSim software platform, which is referred to as the OPUS (Waddell *et al.*, 2005). UrbanSim has been made available as free, open-source software over the web, continuously since 1998, and has been downloaded by thousands of users in dozens of countries. Part of its appeal to users is that the source code is directly available, and if there is a bug, users and developers can find these and fix them. Or users can develop and add their own functionality, or just explore the code to see how it works. This cannot be done with proprietary software, and represents a major obstacle to transparency. With the accountability that public agencies have towards the public, it is increasingly important that they can examine the code that they use to assist in making important public policy decisions, and open-source software makes this possible. One caveat is that if the software is not documented clearly enough, or is poorly organized and structured, this will limit the transparency objective, and it is a significant challenge to develop a sophisticated system that not only provides an intuitive user interface but also provides clear and well-documented source code. This remains one of the areas users have expressed interest in improvements in UrbanSim, as discussed in more detail in the assessment section below.

Empirical validity of models is a very important criterion, and usually the first one on the minds of would-be users of models. The general question they ask is 'does it work?', and what the question usually implies is whether it predicts outcomes that are consistent with what people familiar with the local area can observe. Modellers use the terms calibration and validation to refer to specific processes of adjusting the constants in a model to make it match aggregate observational patterns, and assessing the degree of that match. In transport modelling, calibration is normally accomplished by adjusting the constants in the models until they reproduce to some tolerance the base year traffic counts at selected locations. Other measures such as travel time are usually excluded from these calibration exercises. Further, there has been little practice of comparing simulation results to observed outcomes over time, even though the use of such models is generally to assess projects that may be 30 years in the future. Considering the well-known limitations of four-step travel models in widespread use, and the limited degree of validation that is done on these models, one might wonder why practitioners have put more advanced activity-based travel models and land use models under more intense critical scrutiny, by contrast. Perhaps the answer is that users have become accustomed to the use of standard practice travel models, and have found sufficient ways to work around their limitations. Integrated models and other more advanced travel models (e.g. activity-based travel models) are new to the practitioner community, and therefore have a higher burden of proof to practitioners. Not only should new models perform better empirically but they must be 'worth the effort' in terms of overcoming potentially larger costs in data, computation and complexity.

Multiple strategies have been developed for assessing the empirical validity of the component models in UrbanSim and of the model system as a whole. A modular approach has been developed that allows more controlled testing of the

Table 2. Assessing empirical validity of UrbanSim applications

Level	Approach
Coefficient	Standard errors and t-tests
Model	r-squared or log-likelihood ratio
Model	Prediction–success tables
Model	Sensitivity analysis
Model system	Longitudinal validation
Model system	Bayesian melding

improvements and side-effects of any specific innovation in the model system. The means of assessing empirical validity of UrbanSim applications include those listed in Table 2, ranging from assessment of individual model parameters, to individual equations or models, to the model system as a whole. The last entry in the table refers to a method to calibrate uncertainty in the model system, and is based on research we have adapted to the urban simulation domain called Bayesian Melding (Poole and Raftery, 2000). Examples of using longitudinal validation on historical periods include Waddell (2002) and Sevci Ŝevĉíková *et al.* (2007).

In assessing empirical validity of a model it is crucially important to understand how constrained the model system is by calibrated constants. Some models are too behaviourally simplistic to produce predictions that match observed data adequately and, rather than refining the behavioural content of the models, make extensive use of constants to adjust the predictions to match observed outcomes. Often this is done in a base year context, and it should be no surprise that a model calibrated in this way, and including all of its errors as constants, will reproduce observed data almost perfectly. Unfortunately, it is easy to develop a model in which the constants are doing all the work, and their sensitivity will be heavily constrained by the constants. In the case of UrbanSim, constants or 'K-factors' as they are sometimes called, have been largely avoided. A preferred approach to making heavy use of constants is to identify any bias in the model predictions, and then to add appropriate variables to capture the appropriate effect. Vigorous model validation through visual assessment and local review with planners and others having substantial knowledge of the area is extremely valuable for identifying problems and then generating hypotheses about omitted variables that should be represented.

Ease of use is an important stumbling block for the development and use of any model. In this context, we use the term *appropriation* to represent the degree to which constituents within public agencies bring a model into their operational planning context and integrate it into their planning processes. For a variety of reasons, beginning with the complexity of models and their software implementation, but also due to the difficulties of developing usable input data, urban transportation and land use models have developed a well-deserved reputation as being hard to use. Many travel models have this characteristic, with arcane and cryptic commands and scripts that only a dedicated modeller would have the patience to learn. UrbanSim has warranted this criticism as well, since it attempted to create a model system that would be satisfying in terms of behavioural and empirical validity as its main initial priorities, leaving a friendly user interface initially as a lower priority.

A project of the Maricopa Association of Governments in Phoenix began in 2007, with an objective of developing an intuitive graphical interface that would

Table 3. Ease of use innovations in the UrbanSim GUI

GUI component	Ease of use innovation
General	Interface to variety of SQL servers
General	Variable library
General	Expression language
Data	Tools for GIS, SQL data exchange
Data	Tools for geoprocessing
Data	Data browser and summary
Models	Model templates
Models	Interactive specification
Models	Integrated estimation
Scenarios	Interactive run management
Scenarios	Indicator batches
Results	Interactive indicator construction
Results	Visualization: maps, animations

allow practitioners to appropriate the models and adapt them to diverse local applications. Heavy involvement of agency staff in the development of a user interface, including charting out the user's work flow in developing and using models in an operational context, led to the development of a graphical user interface (GUI) for UrbanSim that users have found to be more intuitive to use, as documented by extensive user-testing of the system (Kriplean *et al.*, 2010). The innovations that were instrumental in this effort include those itemized in Table 3, organized by the section of the GUI to which they correspond.

The GUI is organized into tabs, corresponding to *general* configuration elements, *data* tools and data browser, *models* for creating, specifying and estimating models, *scenarios* for creating policy scenarios and running simulations on them and *results* for generating indicators from results and visualizing them as tables, maps and animations. Data and results can also be exported to SQL databases such as MySQL, Postgres and MS SQL Server and to ESRI geodatabase formats and to post-GIS (geographic information system). A snapshot of the GUI with an indicator map is shown in Figure 2.

Computational performance has been noted as a major challenge to applied integrated land use and transportation modelling. Some existing travel models require run times as long as 36 hours to simulate travel over a single day. Aside for the quip that one should be able to make predictions faster than they can simply be observed in real time, this is really a serious problem for integrated models. To simulate a period of 30 years, even if the interchanges with the travel models are scheduled to run them only every five (simulated) years, the run time would still be 6×36 hours—more than a week of processing, just for the travel models alone, before even adding computation time for the land use models. Clearly these run times are not viable for extensive use as integrated models. Shortcuts like reducing the number of convergence iterations in the travel model may reduce run times considerably, but the impact on robustness of predictions is not well established.

Computational performance has been emphasized in the development of UrbanSim, which represents potentially millions of agents and choices every simulation year. The programming language that UrbanSim is implemented in is Python, which is a scripting language known more for its ease of learning and development than for its speed. However, the system makes extensive use of the

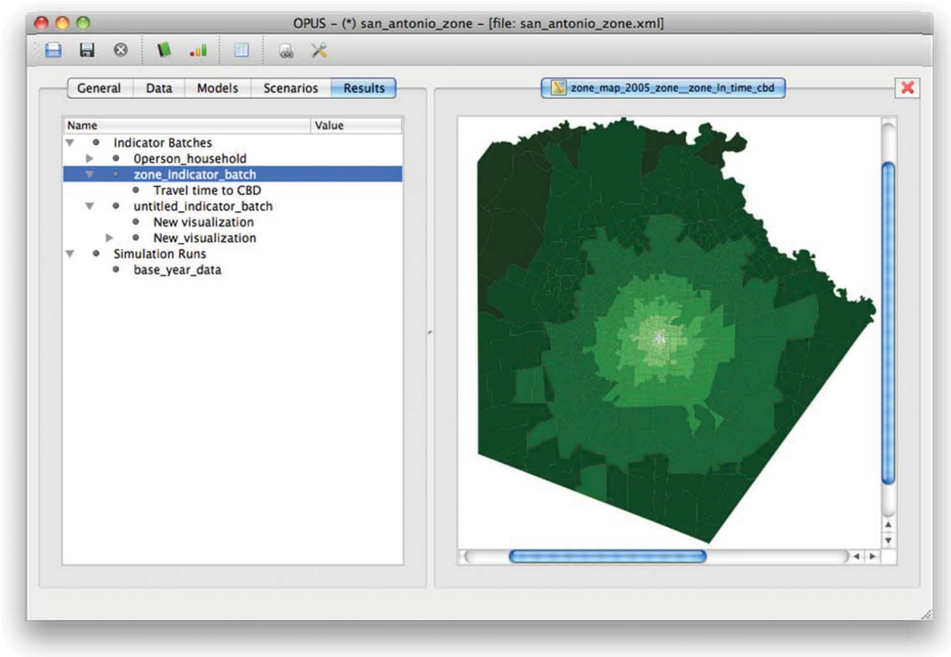

Figure 2. Screenshot of UrbanSim GUI with an indicator map.

Python numeric library Numpy, which provides very efficient computational processing for the model system. With careful software engineering, run times of the model system have been reduced to approximately 30–40 minutes per simulated year for a parcel-level model application in the Puget Sound region of Washington, and to as little as 15–20 seconds per simulated year for a zone-based UrbanSim application for the San Antonio, Texas, region. A San Francisco parcel-level model runs in one to two minutes per year. These times are on a desktop computer acquired in 2009 for well under US$2000. There is definitely more that could be done to improve the run times on UrbanSim, but at this point, the bottleneck is the inordinate run time on the travel models. Work is now underway to find alternative travel model algorithms that are both more behaviourally satisfying and faster computationally.

Flexibility is critical in model development and application because the state of the world is constantly changing. This change applies to every aspect of modelling, including the computing technology (hardware and software) used to implement and run models, theoretical advances, innovations in empirical modelling techniques, improvements in data availability and in tools and algorithms to use existing data more effectively, and of course the inevitable shifting winds of political change, and the evolving questions that models are asked to help inform. A more succinct way to say this is that modellers should be willing and able to change their models when they can be improved.

UrbanSim has gone through many generations since it was initially designed in the mid-1990s. It was implemented initially in Java, and is now implemented in Python, in order to improve the accessibility of the code to modellers and end-users, and to take advantage of fast computational libraries in C and C++, which Python can use. Over time, monitoring the more common adaptations of models has allowed re-engineering the software to support modular construction of models that can be intuitively used by modellers who are not software engineers. The aim is to make the system widely useful by a base of users who probably are not skilled software developers.

The GUI for UrbanSim has been designed to exploit this flexibility and to make it accessible to users. Prior to the creation of the GUI, there was considerable modular flexibility to support experimentation, but the level of expertise and knowledge of the internal structures within the software made this flexibility inaccessible to most users. If a modeller wishes to add a model to the UrbanSim model system, the process begins with creating a model from a template, by right-clicking on the *models* main node in the Models tab, or by duplicating an existing model and changing its configuration. Once a model has been created, the task is to specify it and then to estimate its parameters.

Figure 3 shows a screenshot of the interactive specification of a household location choice model, which provides a simple way to access the variable library and to add variables to the model specification from that library. A similar interface provides a means of interactively creating new variables using the expression language. Examples of the expression language can be seen in these particular variables shown in this specification. It is a simple Python-based syntax, with extensions to allow easy aggregation and dis-aggregation of data within the UrbanSim context. An example of how powerful this expression language is helpful here. Assume a user wanted to define a variable to reflect the average household income in a zone, but the way the data is structured is that households in the data are assigned to a building, and a building is assigned to a parcel, and a parcel is assigned to a zone. This would be a fairly complex join query in a database environment, since the user would have to link households, buildings, parcels and zones. In the expression language, however, this variable can be implement

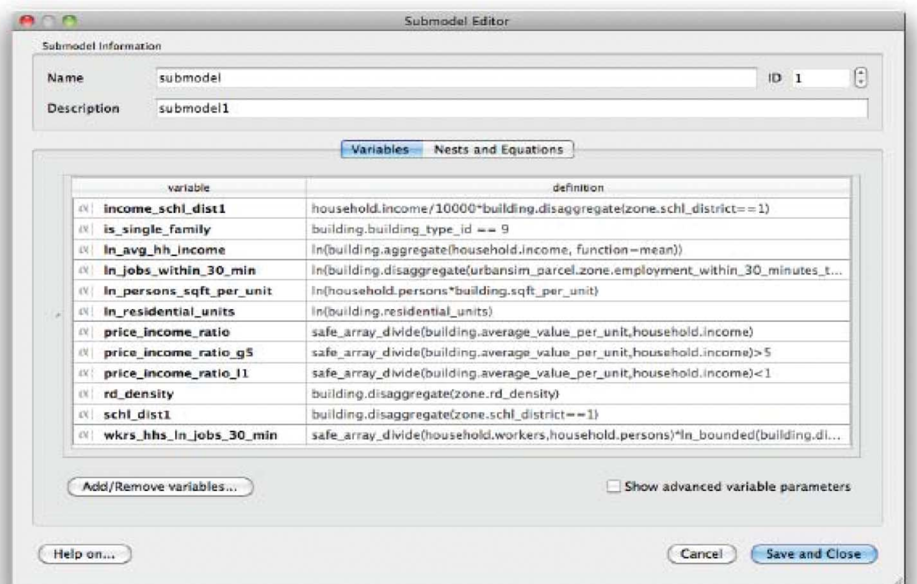

Figure 3. Specifying a household location choice model.

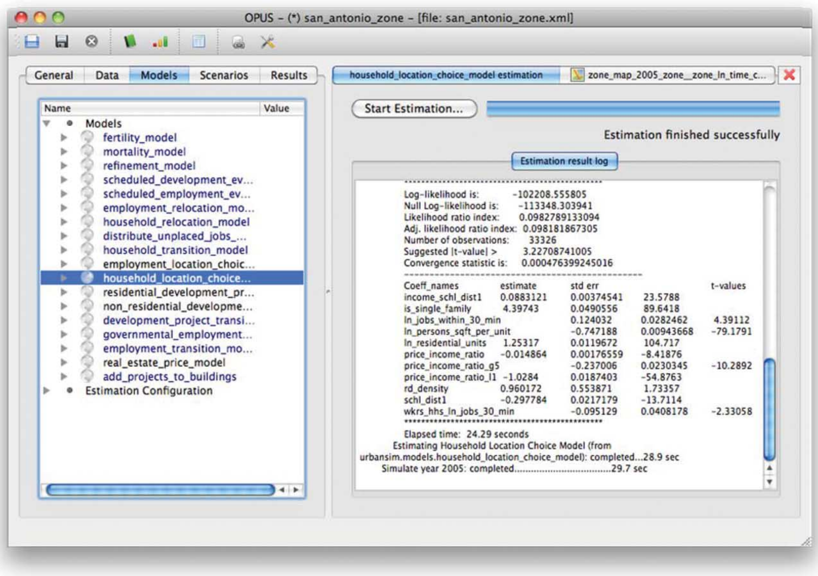

Figure 4. Estimating a household location choice model.

with the following expression: *avg_income = zone.aggregate(household.income, function=mean)*. This syntax is compact, readable and fairly straightforward to learn, allowing modellers to become more efficient in terms of development effort, while executing efficiently due to the use of numerical libraries. By contrast to having to program such variables in a programming language or SQL, it is substantially more accessible to end users.

Estimating a model is done using software built into UrbanSim. UrbanSim can estimate parameters for regression models and multinomial and nested logit models. By internalizing the estimation process, a significant source of error and tedium is removed from the model development process, making modellers more capable of experimenting and refining models. This allows the flexibility of UrbanSim to actually be exercised by end users. Figure 4 shows a screenshot from the estimation of the household location choice model specified in Figure 3.

Data availability and quality are very practical concerns for model implementation. As noted earlier, the vast majority of the full effort to implement a model is invested in data development. Some models (like UrbanSim) have been criticized as being data-hungry, and thereby exposing users to an over-dose of the unpleasant task of assembling and cleaning data for modelling. To these criticisms, there are two responses. First, even aggregate models rely on data that originates from the same detailed data sources we have used in UrbanSim. The fact that the data are aggregated might make the models run faster (we have demonstrated this as well), but does not avoid the messy data problem. Aggregate data only obscure the underlying errors. A response to the messy data problem in the UrbanSim project has been to find effective ways of using disaggregate data by imputing missing values. Early efforts to do this were based on scripts and spatial queries in the GIS environment, for example to impute missing year built values on parcels that lacked that attribute, by drawing on surrounding values to come up with a reasonable value to impute (Waddell *et al.*, 2004). The use of rule-based imputation methods has not been very satisfying, however, since the rules are somewhat arbitrary and the scripts fragile. More recently we have begun using machine learning algorithms to mine messy data and to impute missing values. Results from this work are very promising, and the methods are currently being field tested by a small number of users.

Uncertainty is the final topic addressed in this paper, and is one that is emerging rapidly on the agenda for applied land use and transportation models. Most current models produce point forecasts as predictions, implying that there is no uncertainty. Moreover, most transportation models in practice are based on static equilibrium and are designed to produce one and only one result, and it has historically been considered a strength of these models that they produce stable and unique predictions. However, there are many sources of uncertainty that these models mask. There is measurement error in the input data, uncertainty in the parameters used in the models, or their specification or even their structure. And over longer periods of time, there are many assumptions that the forecasts will be based on which are also uncertain, such as the rate of economic and population growth, the price of fuel and so forth. It should come as a surprise to no one that predicting anything 30 years in the future is a highly uncertain enterprise. To claim the contrary strains credibility. So how then does one defend making point predictions of the future? And why are policy-makers not demanding estimates of uncertainty in the analysis on which they inform their decisions?

Although the science and practice of analysing uncertainty is still emerging, and the concepts of uncertainty are not yet commonly part of the public dialogue about plans and transportation projects, public debates are increasingly engaging questions that are ultimately about uncertainty of the costs, benefits and risks associated with major project investments. Further, we are increasingly bombarded with information about probabilities and uncertainty, and virtually everyone has become comfortable with the concept of uncertainty and its representation in weather predictions. Recent work has begun to emerge on assessing uncertainty in model systems (see e.g. Kockleman, 2002), and methods for calibrating uncertainty in probabilistic models like UrbanSim have been developed to provide more robust treatment of this important topic (Ŝevĉíková *et al.*, 2007). UrbanSim users have regarded this capacity particularly positively, along with flexibility and computational performance, in their assessment of UrbanSim.

Assessment

In this paper, we have explored the challenges to integrated land use and transportation modelling and planning. There are signs that progress is being made, but it is difficult progress indeed, and at times too slow to measure. UrbanSim has been used as a case study in this paper to draw out lessons from more than a decade of experiences in attempting to bridge the gaps between academic research and the messy complications of applying models in the real world. UrbanSim is being used in operational planning processes for supporting the development of RTPs and community stakeholder engagement and visioning by a variety of MPOs (Waddell *et al.*, 2008). A recent survey concludes that UrbanSim is now used by far more MPAs in the USA than any other land use model (Lee, 2009).

In order to obtain the assessments of users of UrbanSim among MPAs in the USA, a small survey was circulated to 13 participants in an MPO UrbanSim user meeting in Berkeley, California, in May 2010. Staff from the following agencies were included: Houston-Galveston Area Council, Lane Council of Governments, Maricopa Association of Governments, Puget Sound Regional Council, Southeast Michigan Council of Governments and Wasatch Front Regional Council. Surveys were distributed by email, and responses could be made anonymously via an online web form, or sent by email. Eight responses were received, most of them reflecting a collective response from the agency. Although the sample size is too small to do any statistical analysis, the responses provide useful indicators of user sentiments. Users were asked a series of questions about their use of integrated land use and transportation modelling using UrbanSim in operational planning processes such as development of RTPs. Respondents were asked what procedures for land use forecasting they used prior to UrbanSim, what challenges they faced in model development, and how they rated UrbanSim on a scale of 1 (extremely poor) to 5 (excellent) on several dimensions. A summary of those responses is provided below, in decreasing order of ranking, with the average rating in parentheses:

- Flexibility (4.25)
- Computational performance (3.88)
- Treatment of uncertainty (3.83)
- Behavioural validity (3.75)
- Empirical validity (3.63)
- Transparency (3.5)
- Ease of use (2.5)

In the comments provided by respondents, it was clear that the flexibility and computational performance of UrbanSim were the most positive assessments, and users valued the generalization of the model system from using grid cells to the use of parcels and buildings. Assessments were also relatively high for treatment of uncertainty, and for behavioural and empirical validity, though in the comments there were concerns raised that the complexity of the software is high for some users, and general difficulties with processing and cleaning parcel level data, lowering their assessment of ease of use and to a lesser extent, transparency. Some respondents had not begun using recent versions of UrbanSim that contain a GUI and templates for creating new models, but those who had begun using these features made positive comments on their contribution to improving ease of use.

A key question on the survey was: 'Have you used UrbanSim in any planning applications (e.g. RTP, scenario analysis, visioning)? If so, please describe what these were, and indicate how successful the application was.' Responses are included verbatim below:

> Yes. Our 2035 transportation plan was developed based on our 2035 land use forecast. Currently, our travel modelling group is working with us to develop their new travel model, which will have significant improvements over the old ones. There are two major advantages with our current model. First, the model can quickly develop new forecast scenarios by adapting new forecast totals. This is very meaningful to our region with quick changing situation. Second, the model can produced very detailed information. This provide strong support for travel model

> developments and make their future changes to activity-based model much easier.
>
> We have produced a 30-year Regional Development Forecast, which was used to produce a 30-year Regional Transportation Plan.
>
> Our efforts with UrbanSim were ultimately successful, although there were many hurdles. In the later stages we ran out of time and had to make a few adjustments to the forecast outside of UrbanSim.
>
> Successfully produced official forecasts for regional transportation plans and conducted county level land use scenario analysis.
>
> We have used US in one iteration of our Regional Transportation Plan. Tool worked well. Results were post-processed to accommodate local input.
>
> We have successfully used UrbanSim in RTP (forecasts released in 2003 and 2006) and in scenario analysis (e.g. constraining supply of vacant land available for development, using county control totals vs. regional control totals, analysing land use impacts of specific projects). UrbanSim was successfully integrated with the agency's travel demand model and use to model and analyse alternatives proposed in the last update to the regional transportation plan update, adopted in May 2010. In this initial application, the analysis focused on the change from a baseline condition—both land use and travel performance measures were assessed as to the direction and magnitude of the change. Metrics used from UrbanSim output were incorporated into the Alternatives Evaluation Report for the plan update (http://www.psrc.org/assets/3698/AppendixD-PolicyAnalysisandEvaluationCriteriaReport.pdf) and included change in population and employment distributions, jobs-housing balance, and building stock that supported estimates of change in energy use, impervious surface and emissions. Overall, the model provided reasonable and intuitive results to the policy scenario inputs when evaluated at the regional change-over-baseline level of analysis.

From user feedback and independent assessment, priorities for further improvement in UrbanSim and the OPUS include:

- continued refinement of a GUI to improve ease of use,
- data integration and cleaning methods to improve the ease of developing usable data for integrated modelling,
- compelling visualization and interactive graphical input capabilities, and
- integration of modelling with visioning processes to move seamlessly from visioning to planning.

The challenges of developing models that are useful in practice remain substantial. Significant progress is being made to address these challenges, and some of the earlier criticisms that emphasized theoretical and empirical realism and computational performance have been addressed to the point that they are now overshadowed by concerns about increasing the ease of use. While further research and development on the validity and computational aspects of the models is surely still warranted, more attention will need to be focused on issues of usability, documentation and information exchange among model users. Integration of models into participatory decision-making processes remains an important goal, but will require significant effort to achieve. The option of relying on informal practice is not likely to be sufficient to address the current and emerging federal requirements for MPOs in the USA, and integrated land use and transportation modelling therefore remains an important area for continued improvement in research and practice.

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