Agent Behaviour Issues Arising with Urban System Micro-Simulation

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A large co-ordinated program of work is underway exploring techniques for integrated land use transport modelling, including elements of agent-based micro-simulation. The intention is to demonstrate the practical viability of these techniques and help provide guidance in their further development and use in policy analysis considering transport policy and the impacts of transport on society. This has given rise to a number of questions about the nature of the behaviour of the agents being considered (including people, households, business establishments and developers) and about potential methods for implementing practical representations of this behaviour. This paper describes the modelling system and techniques being considered, and sets out some of the questions about behaviour and its representation that have arisen together with some of the more promising ideas and approaches being considered for addressing these questions.

1. Introduction

A large co-ordinated program of work is underway exploring techniques for integrated land use transport modelling. This program of work includes the development of an extensive modelling system within a practical environment (for the State of Oregon in the United States) together with the exploration of specific extensions to this system within a research environment (to date primarily at the University of Calgary in Canada). Various elements of agent-based micro-simulation have been included in the development of the practical modelling system. This has given rise to a number of questions about the nature of the behaviour of the agents being considered (including people, households, business establishments and developers) and about the potential methods for implementing practical representations of this behaviour. The intention in the research component of the program is to explore these questions, seeking to develop a greater understanding that would, among other things, contribute to improved practical modelling as the work progresses. It is expected this will translate into improved analysis of transport policy and its impacts on both the transport system itself and the rest of the larger spatial economic system.

The work described here is part of a dramatic and widespread increase in recent efforts exploring the practical use of agent-based micro-simulation techniques in the modelling of one or more components of the larger urban system, which includes both transport modelling and land use transport interaction modelling. Such recent efforts include:

- traffic micro-simulation models representing traffic flows on roadway networks in terms of the locations and movements of the individual vehicles in the flows from one point in time to the next (PVT, 2000; Van Aerde, 1997; Nagel et al, 1998; SAIS, 1999).
- tour-based micro-simulation models, where household travel is considered in terms of the sequence of home-based and work-based tours made by individuals. In such models, mode, destination and time-of-day choices can be influenced by the attributes of entire tours rather than individual trips; non-home-based trips can be integrated into a consistent representation rather than left in a separate (and poorly represented) category; and constraints on behaviour arising with a sequence of decisions in time and space can be included explicitly. (Bradley et al, 2001; Jonnalagadda et al, 2001; Bowman et al, 1999; Bowman and Ben-Akiva, 1997).
- micro-simulation models of developer actions regarding the transformation of vacant land and/or previous buildings into new space for use by households, businesses and other economic activities. In such models, these developer actions are conditioned by specific site constraints, land use regulations and relevant costs and potential revenues (Waddell, 1998a; 1998b; 1998c)
- exploratory research considering the potential use of the tour-based approach with micro-simulation techniques in the modelling of goods movements and service deliveries (Hunt and Morgan, 2001).
- It would seem that the dramatic increase in these efforts listed above is encouraged at least in part by the potential benefits of micro-simulation, including:
- reduced computational burdens compared to those arising with the use of aggregate techniques considering large multi-dimensional fractional-probability arrays
- flexibility in the aggregation of results in policy analysis
- the potential for a more complete accounting of constraints on individual agents; for example, once one member of the household has been allocated the household car then the car is not available to the other members
- higher resolution in the representation of conditions influencing agents
- the potential for explicit representation of heterogeneity in the attitudes and sensitivities across the population(s) of agents being considered.

It may also be that the mere ability to develop such micro-simulation techniques - given the much greater availability of large-capacity, low-cost computing power - has helped encourage the exploration of their potential use. In any case, the dramatic increase in the use of micro-simulation techniques increases the relevance of the questions about the nature of the behaviour of the agents considered here.

The design of the practical modelling system that has been developed in this work as it currently stands is described in Section 2. Some of the questions about behaviour and its representation that have arisen together with some of the more promising ideas and approaches currently being considered for addressing these questions in the work at the University of Calgary are outlined in Section 3. Some conclusions are offered in Section 4. As such, the paper sets out various elements and ideas that together have the potential to provide a starting point for discussions about a broad research agenda for a network of researchers concerned with the interactions among environment, urban form, land use and transportation and regional economics. The aim of the paper is to engender such discussion, thereby helping set out further research with a broad and ambitious scope that is nevertheless grounded with direct connections to an existing, practical modelling application and thus has the potential for immediate practical implications.

2. Model framework

The practical model framework is a combination of 7 integrated modules, some aggregate representations relying on equilibrium solutions and others fully dynamic dis-equilibrium agent-based micro-simulations. The system evolves through time in discrete year-by-year steps. Household demographics, residential location decisions, employment and associated training choices and daily activity patterns are represented using micro-simulation. Travel tours by household members and commodity movements are also micro-simulated. Each trip is loaded onto transport supply networks link-to-link with minimum path assignment using randomly assigned utility function sensitivities that allow dispersion in travel choices. A general form of spatially-disaggregated input-output model is used to identify patterns of spatial locations and interactions among the different economic sectors, including the interfaces with households, in an aggregate treatment. Area-wide levels of production activity and population in-migration are established using an aggregate regional economic model. A Monte Carlo treatment of developer actions in small area grid cells is used to simulate changing development patterns.

2.1 Treatment of space

The model covers the entire State of Oregon and a ‘ring’ for about 50 miles just beyond the state boundaries to the north, east and south as indicated in Figure 1. This area is divided into a co-ordinated system of zones, link tributary areas and grid cells as depicted in Figure 2. These different divisions of space and related network conditions are used for different parts of the model, reflecting the different perceptions and processes involved.

Each of these three forms of division covers the entire model area. The grid cells are the smallest, and they nest completely into both of the other two. That is, all zone boundaries and link tributary areas are consistent with grid cell boundaries and there is a whole number of grid cells in each zone and link tributary area.

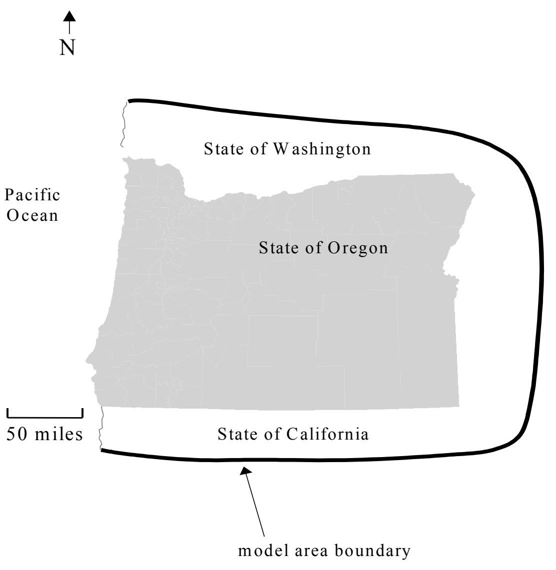

Figure 1: Area covered by model

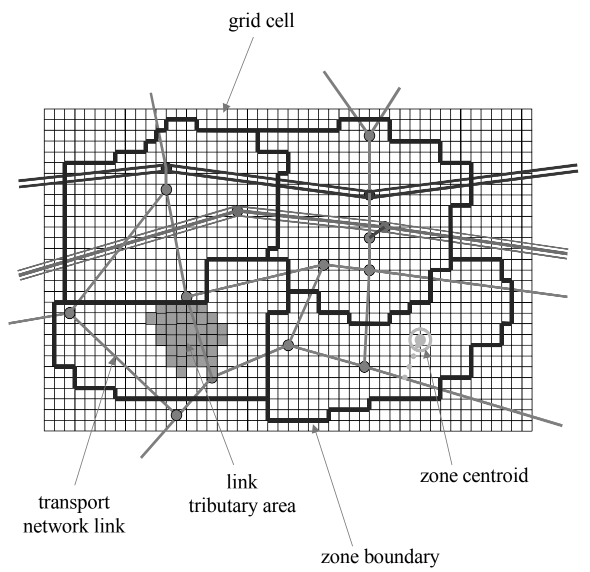

Figure 2: Illustration of co-ordinated zones, grid cells and link tributary areas used in the treatment of space

The zones are roughly on the order of traffic analysis zones, and are connected to the transport supply networks using centroid connectors. There are about 3,200 zones covering the entire model area.

The grid cells are squares of land sufficiently small enough that just one type of developed space (one category of building floorspace) can be attributed to a given cell without substantial loss of accuracy. The current thinking is that 30m x 30m cells within and near to built-up areas and 300m x 300m (or even larger) cells in more wide-open spaces are acceptable in this regard. The current estimate is that there are about 14.5 million grid cells covering the entire model area.

The link tributary areas are the areas containing the origins and destinations of the trips feeding the corresponding links in the transport system, and there is a separate, mutually exclusive and collectively exhaustive set of tributary areas for the set of links constituting a network for each mode.

2.2 Treatment of time

The model steps through time in a series of one-year steps that allow the entire system to evolve as indicated in Figure 3. The representation for year t+1 is influenced in part by the conditions determined for year t, which provides for explicit representation of various lagged effects and system inertia.

As explained below, an equilibrium is used for some aspects of the representation but not others. In addition, some of the simulation processes within the model involve time steps much shorter than one year, and therefore are performed multiple times during a given 1-year step.

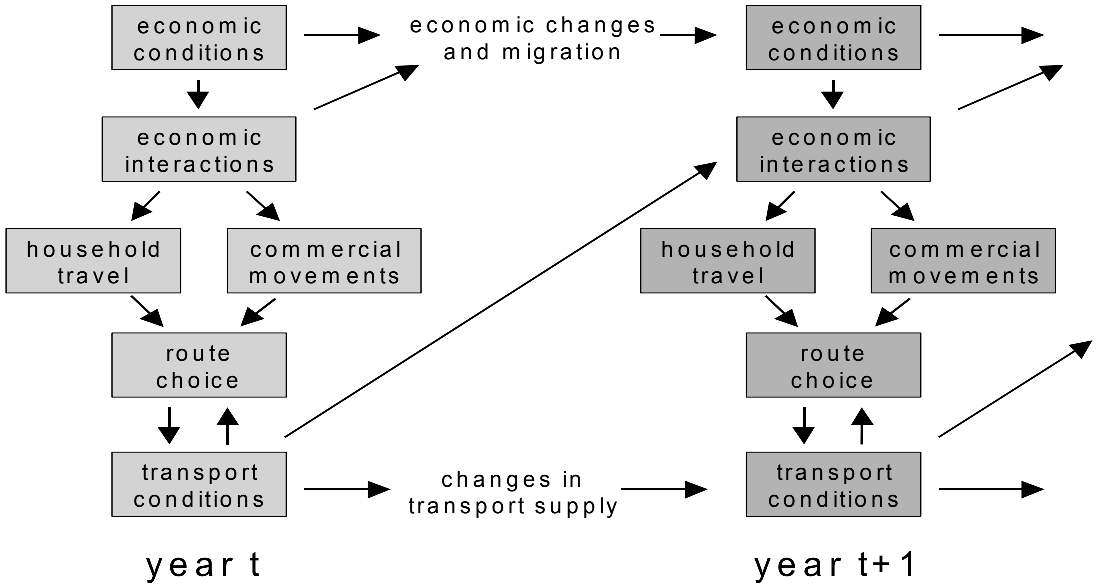

Figure 3: Process used to step the model through time

2.3 Representation of system behaviour

The behavioural representations in the model are based on utility values. In particular, the aggregate quantities considered in the aggregate components of the model are allocated among alternatives according to utility values and the individual actors considered in the disaggregate components of the model react to utility values.

Five different categories of utility value are defined for use in different components of the model. These differ in terms of how they are determined and how they are used.

With regard to how they are determined: a particular utility value is the dependent variable of a utility function that operates on sensitivities together with attribute values, as follows:

$$U_{i,a} = f(\alpha_i, X_a) \quad (1)$$

where:

- i = index representing individuals
- a = index representing alternatives
- $U_{i,a}$ = utility determined for alternative a for individual i
- α_i = vector of utility function coefficients indicating sensitivities of individual i to attributes of alternative a
- X_a = vector of attribute values for alternative a.

The five categories of utility value are as follows:

- 'Rutility' values: These are used for allocations of aggregate quantities. The attribute values, Xa, are average, zonal or typical values. The sensitivity values, αi, are typical values for the category of aggregate quantity being allocated. The 'R' placed before 'utility' stands for 'representative'.
- 'Zutility' values: These are used for agent-based micro-simulations of individual household and person decisions. The attribute values, Xa, are average, zonal or typical values, but the sensitivity values, αi, are specific values assigned to the household or person. In this case, differences in the sensitivity values among a set of agents gives rise to dispersion in the behaviour of the set. The 'Z' is for 'zonal'
- 'Iutility' values: These are used for network path selection for aggregate, zone-to-zone trip flow assignment. The attribute values, Xa, are specific link values, and the sensitivity values, αi, are aggregate values assigned to the flow being assigned. The 'I' is for 'interchange'.
- 'Lutility' values: These are used for network path selection for individual trip assignment. The attribute values, Xa, are specific link values, and the sensitivity values, αi, are specific values assigned to the trip-making agent. The 'L' is for 'link'.
- 'Cutility' values: These are used for micro-simulations of land development decisions. The attribute values, Xa, are specific grid cell values, and the sensitivity values, αi, are typical values assigned to the developers as a single category. The 'C' is for 'cell'.

The model represents the behaviour of the full system using a set of 7 separate but highly connected modules that cover different components of the full system. This set of modules and the flows of information among them are shown in Figure 4.

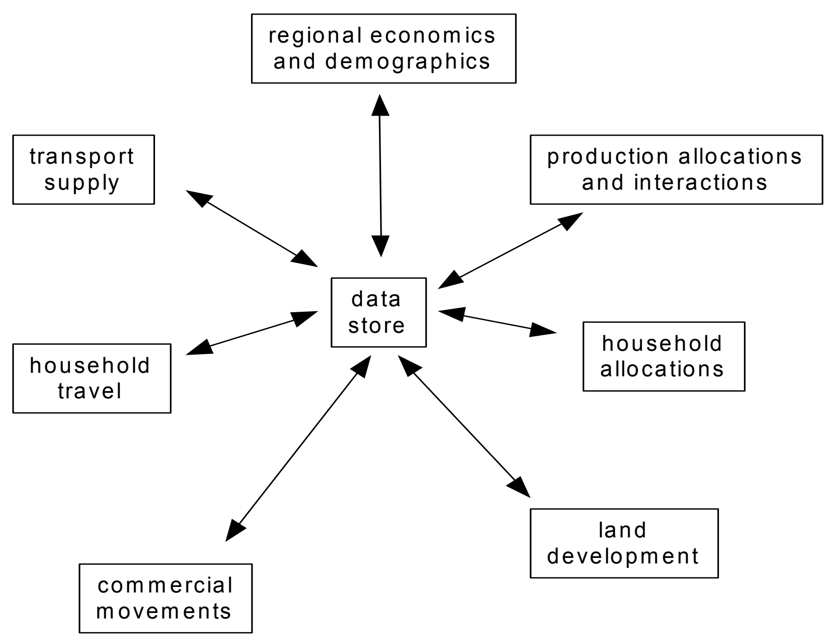

Figure 4: The modules in the model and the flows of information among them

This modular design allows a sort-of ‘plug&play’ upgrading and flexibility. It also allows different approaches to be used for different components, such as:

- fully dynamic vs quasi-dynamic;
- equilibrium vs dis-equilibrium;
- aggregate representation of the behaviour of flows vs disaggregate representation of the behaviour of individual agents; and
- statistical reproduction of patterns vs simulation of processes.

Each of the modules indicated in Figure 4 is described further below:

Regional Economics and Demographics

The regional economics and demographics module provides the rest of the model with regional control totals for production by economic sector, imports and exports by economic sector, employment by labor category, in-migration, and payroll by sector for each year. It requires exogenous forecasts of United States national production, employment, and population as inputs. It includes simple macroeconomic models of sub-national regions to the north, south, and east of the model area to assist with trade flow predictions.

A combined input-output and econometric model is used, based on the coupling strategy identified by Rey (1998) and various approaches and refinements developed for the Washington Project and Simulation Model by Conway (1990). A set of simultaneous linear equations representing the input-out put structure of the model area economy are used to predict the dollar value of production by sector. Additional linear equations for various components of final demand and for the labor market are solved simultaneously with the input-output equations.

Production Allocations and Interactions

The production allocations and interactions module determines for each year:

- The distribution of production activity among zones;
- The consumption of space by these production activities;
- The flows of goods and services and labor from the location (zone) of production to the location (zone) of consumption; and
- The exchange prices for goods and services, labor and space.

This is done using an aggregate treatment, where the quantities of production, the consumption of space, the flows of goods and services and labor (called 'commodities') and the exchange prices are determined for the entire economy, with the households located as determined in the household allocation module in the previous year.

The theoretical basis of the aggregate treatment of the economy is an extended form of the spatially-disaggregated input-output approach used in MEPLAN (Hunt and Simmonds, 1993) and TRANUS (de la Barra, 1998). Figure 5 provides a depiction of the approach. Production activity by economic sector is quantified in terms of dollar value of production, and production functions based on the technical coefficients in the input-output 'make' tables are used to determine quantities of input commodities required, including goods and services, labor and space. Commodities flow from production locations to 'exchange locations' to consumption locations. Exchange locations represent the places where exchange prices are determined and where commodities are transferred from the seller to the buyer, thereby allowing an allocation of transport costs. Flows of commodities are allocated from production locations to exchange locations, and from exchange locations to consumption locations according to logit formulations that take into account the exchange prices and the relevant transport costs. This is in contrast to the treatment in the standard spatially-disaggregated input-output approach, where it is the demand for additional production that is allocated, rather than the flows of commodities, and where the prices are always determined at the production location. The introduction of the concept of exchange locations in this way permits a much more flexible range of possible representations, and allows a much more realistic treatment of labor markets in particular.

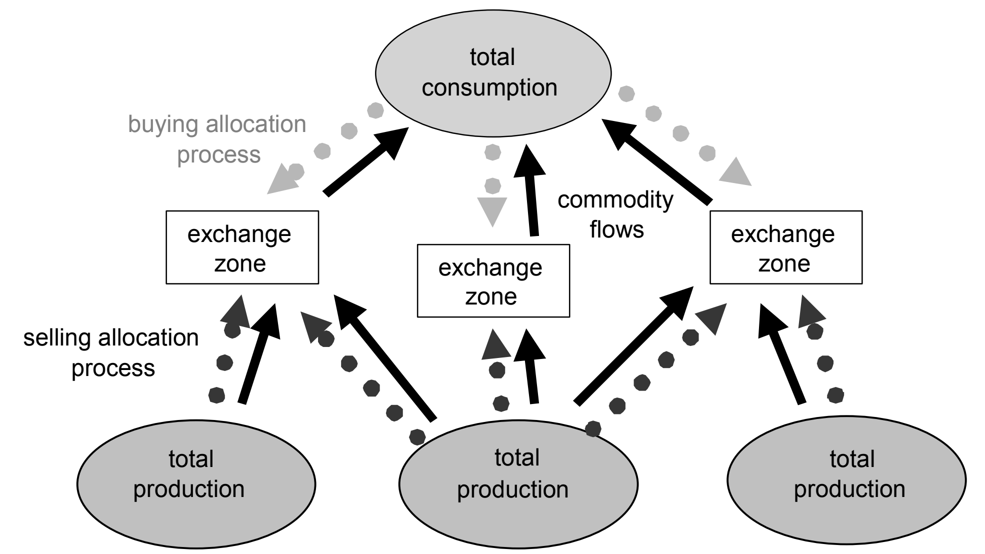

Figure 5: Depiction of the generalized, extended form of spatially-disaggregated input-output approach used in the production and allocations and interactions module

For all economic sectors other than households, the total production activity in the sector over the entire model area for each year is determined in the economic and demographic module. This total is allocated among the zones in the model area using a logit formulation with a utility function that includes terms representing the impacts of:

- Lags and inertia;
- The Rutility (including transport costs and exchange prices) associated with selling output commodities, based on the zone-to-zone attributes for a representative time slot and fixed utility function coefficients;
- The Rutility (including transport costs and exchange prices) associated with buying input commodities;
- The utility of business travel; and
- Location-specific taxes and subsidies.

The consumption of goods and services and labor and the consumption of space in zones by production activities is elastic with respect to the buying disutility, which is influenced by the exchange prices that are available. The production of labor by households is also elastic with respect to the selling utility - with a function that constrains the ability of labor supply in each exchange zone to change beyond certain limits in a given year. The exchange price for a commodity at an exchange location is adjusted in response to the levels of aggregate demand versus the aggregate supply at that exchange location. An equilibrium solution is identified by adjusting exchange prices and reallocating production activities and flows of commodities in an iterative process to convergence. It is certain that the equilibrium solution that is identified will not be beyond the capacity of the economic system because the production totals have been established in the economic and demographic module.

Household Allocations
The household allocations module determines for each year:

- Changes in household composition, in the characteristics of household members and in the characteristics of households, including the effects of demographic and economic processes;
- The specific sensitivities (relevant utility function coefficients) of household members and households;
- Household actions regarding home locations; and
- Residential space use quantities and prices.
- The vector of inputs for each household;
- Household car ownership changes;
- The employment/SOC status and workplace location (zone), as relevant, for each household member; and
- The school status and school location (zone), as relevant, for each household member .

This is done using micro-simulation, where there is an explicit consideration of each individual household in each time period. In general, Monte Carlo simulation is used to assign specific conditions to each household, with the selection probabilities for alternative possible conditions based on either (a) exogenously specified conditional distributions or (b) choice probabilities provided by models of choice behaviour that include an explicit representation of influences on decision-making.
The theoretical basis for the representation of household behaviour in the determination of household composition and household conditions is reflected in the processes used to assign the specifics to each household and in the way these processes are combined. In some cases the specifics for each household are assigned by random sampling from aggregate distributions, which is in essence a statistical approach. In some cases the specifics for each household are assigned using probabilities determined by a logit formulation with utility functions providing Zutility values, which means that the process can be viewed to have a basis in random utility theory.

Land Development
The land development module determines the changes in space from one year to the next.
The supply of (developed) space in a particular year is fixed, and the other modules operating for the year operate given this fixed supply. These other components determine a price for each category of space in each zone, and the primary task of the land development module is to adjust the quantity of space over time in response to changes in price. This is done in a highly disaggregate manner, one grid cell at a time.
Three decisions are simulated for each grid cell. The first is whether the cell should be redeveloped or not. The second is the choice of the category of space that the cell should be

redeveloped into. The third is the quantity of new development in the cell. These three decisions are represented using logit models. The utility functions for each of the alternatives in each choice set are based on rents and vacancy rates established in the equilibrium model.
The land development model is behavioural, simulating the decisions of land owners regarding how to improve their properties. Land owners (developers) make their decisions based on current prices and vacancy rates, leading to behaviour consistent with the notion that developers react to changes in conditions because they expect future conditions to be similar to the most current conditions.
The changes to grid cells are assigned using Monte Carlo selection where the selection probabilities are determined using logit formulations with Cutility values that are functions of the current space type, the number of years since the more recent change, the zonal prices for space of difference categories and both zonal and model-area-wide vacancy rates. This leads to a patchwork of different space types in zones and in link tributary areas that helps simulate the diversity of trip origins and destinations. In addition, the potential also exists to further influence this process and to adjust the results using information about both (a) proximity to specific transportation infrastructure and (b) the content of adjacent cells (possibly applying forms of cellular automata).

Commercial Movements
The commercial movements module determines the truck movements arising during a particular representative workday for each year.
A fully disaggregate list of truck movements is synthesized, providing the following for each truck movement:

- Vehicle type (light single-unit, heavy single-unit, articulated);
- Starting link;
- Ending link;
- Starting time;
- Commodity carried; and
- Trans-shipment organization.

Commodity flows between aggregations of zone pairs are considered in turn.
For a given commodity flow and aggregation of zone pairs, a shipment size of that commodity is randomly selected from the Commodity Flow Survey dataset and the flow is reduced by this amount. The vehicle type, starting time, and trans-shipment information for the shipment is synthesized taking into account similar shipments and vehicle movements being made nearby and this information is added to the list being generated by the model. The origin and destination of the movement are attributed to particular grid cells in each zone by randomly selecting from the set of cells with space types consistent with the commodity being shipped. In this way the link for the start of the trip and the link for the end of the trip are identified for each trip, as required by the transport supply module.

Household Travel
The household travel module establishes a list of the specific individual trips made by members of households during a particular representative workday for each year, providing the following for each trip:

- Starting link;
- Ending link;
- Starting time;
- Tour mode;
- Vehicle occupancy if automobile mode;
- Utility attribute coefficients defining personal preferences of traveler(s) for this trip; and
- Non-network related utility components.

The process starts by assigning each household member an activity pattern for the day. The sequence of activities undertaken by the household member is identified using a Monte Carlo process where the selection probabilities are based on a logit function using Zutility values as inputs. The activities in a given pattern are then assigned durations using a Monte Carlo process, with the selection probabilities based on hazard models that are functions of the general nature of the rest of the activity pattern assigned the person, the age and gender of the person, household income, work and school status, expenditure level and transport accessibilities at both the home location and the workplace location as appropriate. Following this, each home-based tour and work-based tour is considered separately. The tour is assigned a 'primary' destination location (zone) and a tour mode, and each trip is assigned a trip mode using Monte Carlo processes with the selection probabilities determined using logit formulations with Zutility values that include composite utilities for the lower level trip and tour mode alternatives in the choice model nesting structure.

The start time of each trip is then established according to the durations previously assigned the corresponding activities. The origin and destination of each trip are attributed to particular grid cells by randomly selecting from the set of cells with space types consistent with the activity at the stop. In this way the link for the start of the trip and the link for the end of the trip are identified, as required by the transport supply module.

Transport Supply

The transport supply module determines transportation network loadings and transportation network attributes given transport demands from the household travel and commercial movements modules. This is done as a 'micro-assignment', at the level of individual vehicles and individual travelers (using public transportation, using their own personal vehicle, or grouped with other travelers sharing a vehicle).

The primary mode of the trip dictates which network links are available for the trip. Road-based vehicle trips are loaded to the road network and person-based transit trips are loaded to the transit service network and related walking networks separately and then the results are combined by adding the road-based transit vehicles to the road network. Walk-based and cycle-based trips are loaded to walk and cycle networks derived from the road network using link distances, with no impact on congestion levels.

For the loading to the road network, the vehicle trips (including both those established in the household allocations module and those established in the commodity movements module) are first organized into an aggregate zone-to-zone trip table and this used to establish an aggregate solution that becomes the starting point for the micro-assignment. For the aggregate solution, the Frank-Wolfe assignment process (Ortúzar and Willumsen, 1990) is used (with aggregate flow assignment sensitivities used to develop Lutility values for the links) for a sufficient number of iterations to ensure that an acceptable level of equilibrium convergence has been reached. Initial testing has indicated that this takes about 15 iterations.

Based on this equilibrium set of link flows and travel times, the micro-assignment procedure is implemented. Micro-assignment involves loading the individual trips (with individual route choice sensitivities represented in the Lutility values calculated for the links) from specific origin point locations to destination point locations one at a time in order to obtain a dispersion of trips consistent with the range of sensitivities in the population and in order to avoid artificial overloadings of trips at the points where the centroid connectors join the road network. To ensure conservation of the total number of trips and the corresponding network loadings, it is necessary to remove the portions of a single trip from paths built during the Frank-Wolfe solution process when loading a new trip in micro-assignment.

Road network assignment is typically the most computationally burdensome component of running an integrated land use transport model, and this model is no exception. The model considers as many as 12 million trips in its list each year, which requires several hours in the current setup. This leads to rather long run times overall, and efforts are underway to identify ways of reducing these run times, including parallel processing, reorganization of the computer code, and the possibility of running the transport assignment less frequently than every year.

The loading to the transit network is done using a form of the optimal strategies procedure as implemented in the EMME/2 modelling software (INRO, 1996). With this procedure all 'reasonable' paths through the transit network are identified, and the flow of travelers from origin zone to destination zone is allocated among these paths according to their relative attractiveness. The process starts with the micro-assignment, where each trip is considered in turn. Lutility values for the transit network are determined for the trip (using the specific sensitivities assigned the corresponding traveler) and the optimal strategies process is used to identify the alternative reasonable paths along with the probabilities of use of each of these paths. These probabilities of use are then used to select a specific path for the trip using a Monte Carlo process. The loads on all the transit links in the selected path are increased by 1 and then the next trip in the list is considered.

The walk and cycle trips are then loaded one at a time using a path selection process like that used for the road-based trips. The results of the road network assignment are used and the walk and cycle trips are accumulated on links as the process continues.

3. Questions arising

Some of the questions about behaviour and how it is represented that have arisen with the work on the development of the model framework are discussed below under specific headings.

3.1 Search processes

The current modelling system relies heavily on the discrete choice behaviour model – the logit model in particular. The logit model is based on a set of fairly strong assumptions about decision-making, including optimization, compensatory evaluation and full information. While it is true that the agents need only behave as if these assumptions were true in order for the modelling system to provide accurate forecasts, it nevertheless is troubling that such strong assumptions constitute such a large part of the theoretical foundation of the system. It seems pretty certain that agents do not always seek out the single best optimum, at least sometimes do not feel that the attractive aspects regarding one attribute compensate for the unattractive aspects regarding another, and do not have full knowledge of all of the available alternatives. Rather, it seems much more likely that the actual behavioural mechanism used by agents is some form of search process that seeks to identify a satisfactory of indirect utilities, let alone the log-sums of such utilities.

The use of such a set of rules in the model would provide a representation of the actual behavioural mechanisms, and thus provide a representation with greater 'fidelity'.

One of the potential benefits of the micro-simulation approach is the potential to use such a set of fairly simple rules directly for each agent, with the resulting aggregate model behaviour then being something that emerges from the combined results. This means that the aggregate model has the potential to exhibit all sorts of 'unanticipated' responses beyond those that would arise when the 'smooth' behaviour of the logit model is applied to each agent, including various behavioural regimes and related feedback signals and synergistic effects. This would provide a greater potential to learn about the system from the model, rather than requiring that anticipated system behaviour be imposed on the model.

On another front, with some of the choice situations considered in the modelling system, the agent faces a very large number of alternatives. The calculation of the full set of utilities for all of these alternatives with the implementation of the logit model in these cases imposes a very large calculation burden. The agent certainly doesn't perform this very large set of calculations, only – hopefully – 'behaves as if he does'. The use of a simple set of rules that mimics actual behavioural mechanisms would greatly reduce the amount of calculations required, which has very large practical implications for such models.

This leaves questions about the nature of the search processes used by agents in different contexts, and about the sorts of rules regarding such search processes that would be appropriate to use in models. For example: To what extent do agents conduct on-going searches for improved circumstances rather than make discrete choices at pre-specified intervals? How do agents identify potential options? To what extent do agents use non-compensatory elimination rules rather than compensatory utility-based evaluations? What are the roles of both money and time budgets?

Previous research has explored some of these questions. But the potential use of micro-simulation has renewed their relevance, and perhaps helped define the most appropriate directions for further enquiries.

One idea being explored (Abraham and Hunt, 2002) concerns the identification of potential options: that households continually consider elements of the lifestyle patterns of a fairly small set of reasonably similar co-workers, neighbours and acquaintances, and are more likely to switch certain elements of behaviour when an alternative with a significantly better utility than their current selection is encountered. At the aggregate level, ideas and behavioural changes are seen to 'diffuse' through society with such a mechanism.

3.2 Business establishments

The current model uses an aggregate representation of production activities in its treatment of the economy apart from households and space. There are flows of production (outputs) and consumption (inputs) values, including labour, without any explicit representation of firms or businesses as separate agents. Thus, the treatment of the economy does not enjoy the benefits associated with an agent-based micro-simulation treatment that are realised with regard to households, as follows:

- Flexibility in aggregation;
- Potential to reduce computational burden with the use of more simple behavioural rules;
- Ability to have more complete accounting of agent-related budgets (such as the allocation of family cars);
- Potential for the explicit treatment of actual behavioural mechanisms, including:
  - non-linear and non-compensatory rules; and
  - finer resolution in the representation of conditions and alternatives;
- and the associated potential for 'unanticipated' aggregate emergent behaviour; and
- Ability to use sensitivity variation as a source of dispersion.

One thrust of research work underway (Khan et al, 2002; Abraham and Hunt, 2001) concerns the potential for an agent-based micro-simulation treatment of business establishments analogous to that used for households. A range of questions arises, including: How do business establishments appear, develop (grow or decline) and/or disappear? How are production technologies (in the form of input-output technical coefficients) distributed among such establishments? Do reasonable aggregate development patterns (such as those identified in Central Place Theory (Christaller, 1933; 1966) and by Alonso (1964) emerge from these treatments? Can acceptable aggregate market behaviour be seen to emerge from a representation of the interactions among disaggregate bids for each of a set of commodities and services forming the inputs and outputs of business establishments? What are the relevant aspects of the agent behaviour in this context? How can the much greater amount of variation among establishments and the resulting much greater data requirements compared to households be handled? Finally, do the benefits of the improved modelling justify the level of effort required to develop such a representation?

Again, previous research has explored some of these questions to some extent. But the emphasis has been very uneven. A few have been the focus of considerable effort by economists. Others have received virtually no attention.

One idea being considered uses the concept of a 'proto business establishment' that is assigned a set of technical coefficients using a genetic algorithm in an attempt to simulate the emergence of new business ideas and new technologies. In a given year a range of these proto business establishments are generated. The business success of each is evaluated in terms of the production utility it would realise if it had operated for a year – without including its effect on markets – and those with higher utilities are more likely to appear as new establishments. Part of the greater challenge regarding such 'firmographics' (concerning the appearance, development and/or disappearance of business establishments) is the lack of the sorts of constraints and influences that exist with people and households: A household has to have at least one person in it, and when a household disappears all the former members must 'go' somewhere, either they die or they go to another household. Age and lifecycle stage help inform the probabilities of such transitions. But a business establishment can emerge without any employees and 'age' has little or no meaning.

3.3 Motivations

In the current modelling system individuals select activity patterns according to a logit choice framework. There is no explicit motivation for the selection of pattern and what it contains apart from the optimization of the indirect utility that is implicitly associated with the pattern as part of the discrete choice theoretical framework. In reality, people undertake activities and develop activity patterns for a range of explicit motivations. Maslow's (1998) hierarchy of needs (ranging from 'physiological' to 'safety' to 'belongingness and love' to 'esteem' to 'self-actualization') is perhaps relevant, and there is considerable research that has been done on the nature of motivations. The potential benefits of a more explicit representation of the motivations for activities as a replacement for the choice modelling framework are covered in general in the section above concerning choice processes and need not be repeated here. But it should be noted that in one sense the argument being made here is an extension of the one that has been made on behalf of the need for activity models. That is, it is argued that representations of activity patterns – so called 'activity models' – are needed as a replacement for traditional trip-based models because trips to not arise of their own accord and the 'underlying' activity patterns must be taken into account in order to model trips more completely. The idea here goes one step further: activity patterns also do not arise of their own accord, rather they arise as the result of motivations – presumably to satisfy different needs.

A series of questions arises: Can Maslow's hierarchy of needs or some modification or extension to it form the basis for the identification of relevant and useful motivations for behaviour and resulting activity patterns? Are there relevant budgets and/or diminishing marginal returns associated with the time and effort spent on activities and/or the satisfaction of needs that can be used to develop a set of organizing principles or to help identify triggers for certain activities and/or activity patterns? And will there be increases in the benefits associated with improved modelling that will justify the additional effort required to implement a representation of the role of motivations in the determination of activity patterns?

The nature of motivations and their influences on behaviour has been an area of ongoing investigation within the social sciences, and efforts should be made to draw more on what has already been established in that work.

One idea being considered in this regard is the notion of 'projects' (Miller et al, 2002). People are deemed to take on projects in order to satisfy needs and thus must perform a series of activities related to the projects. For example, a family decides to have a dinner party with friends. This dinner party is a project for the family and their friends that is a response to the 'belongness and love' need more than the 'physiological' need. It requires a series of shopping expeditions and, ultimately, the social-recreational visit, in order to occur and these specific activities have to be incorporated into the participants' activity patterns.

Another aspect of activity patterns being considered (not in Calgary, but by another part of the MCRI network to which those in Calgary belong) is the nature of the scheduling process, and the extent to which the activities within an individual's activity pattern are pre-planned versus spontaneous over a period of several days (Doherty and Miller, 2000; Doherty et al, 2001). It is expected that this work will contribute to the development of a more complete understanding of the factors influencing activity patterns.

3.4 Perception of space

Space is a fundamental component of the system being modelled, concerning both the areas occupied by activities and the distances separating activity locations. In the current modelling system activity locations are represented by the discrete zones or cells containing the locations and the selection of locations in various contexts is handled as a discrete choice among the corresponding zones or cells, again using logit choice models. Consequently, all of the strong assumptions involved with the use of logit models as identified above concerning agent choice behaviour generally – regarding optimization, compensatory evaluation and full-information – are made with regard to spatial choices in particular.

Clearly, these strong assumptions are particularly inappropriate in the context of locations and the perception of space overall, where distance plays such a key role regarding what is acceptable as an alternative and what is known about the available alternatives. Given the key role that space plays in the system, a reliance on these assumptions in the representation of spatial choice would seem to be particularly inappropriate. Further, because there are so many zones and the logit formulation considers them all, the calculation burden is particularly great in this context. It follows that much would be gained in term of both greater fidelity and reduced computational burden with the adoption of a representation of the perception of space and location alternatives within space that is closer to the actual behavioural mechanisms acting for different agents.

The relevant questions include: How do agents perceive the available alternatives in the context of locations in space? How does the accuracy and/or precision of knowledge about locations vary across space? Is there a strong relationship between search cost and distance (or travel generalized cost) from some relevant point of reference that could be used in the representation of a search process? More specifically, should distance from some point of reference be used in some way to filter alternative locations or adjust the way in which the agent perceives (or groups) alternative locations? What are the relevant points of reference for different agents in different contexts, and how are these determined and/or influenced?

Some research work has been done by others concerning the perception and representation of space in different contexts, from the seminal investigations of ‘mental maps’ and images of place in different situations (Lynch, 1960) to the development of artificial intelligence approaches to the transformation of physical space into cognitive maps (Yeap, 1988). A concerted effort needs to be made to draw on the results of this range of work in the development of representations of decision-making in a spatial context for agent-based micro-simulation models of this sort, where space is a key component. This is true not just for land use transport interaction models, but also for transport demand models – given that space, in terms of the distances between activities, is a key component in these models as well – so the potential implications are even more widespread.

3.5 Evolution of sensitivities

The current modelling system uses utility function coefficients to represent sensitivities to the attributes of alternatives in a range of different contexts. With Zutility values in particular these coefficients representing sensitivities are specific values assigned to the individual agent (household or person). This provides an opportunity to allow these values to change over time in response to influences on the agent – thereby providing representation of the evolution of these sensitivities, reflecting how they might be influenced by exposure and experience, learning and even advertising.

This gives rise to questions about the nature of changes in such sensitivities. For example: How does continued use of LRT, or perhaps even just continued living near to an LRT station, impact an individual’s sensitivity to LRT ride time over the years? More generally: Does exposure to specific alternatives alter sensitivities to the attributes of these alternatives? Are their trends or ‘drifts’ in such sensitivities towards specific values over time? Do

awareness campaigns and other efforts at public education have any impacts on sensitivities, over both the short term and the long term?
Investigations in this regard have centred on sensitivity tests concerning the extent to which the behaviour of the modelling system is impacted by different assumptions about the strength of such influences on sensitivities.

3.6 Public agencies

The current modelling system requires that all policy elements be input explicitly on an element by element basis each. Thus, if there are any policy responses to changing conditions by public authorities, the analyst must determine these off-line and input them before the model is run for the corresponding year. For example, if a portion of land in a particular area is to be released for single family development, then the analyst must specify the additional amount of land available in each zone in the area. If the policy being tested is that further land will be released in subsequent years only if there is further demand, then the analyst must monitor the results of the model in order to see if there is such further demand, and adjust accordingly the specification of the additional amount of land available each year. This is likely to present several practical difficulties. It could be very slow and labour intensive. It could be difficult to interpret, and there could be difficulties with consistency in that two different analysts might perform differently and it could be difficult to interpret.
One idea being considered in response to these practical difficulties is the addition of an ‘authority agent’ that would monitor the results of the model year-by-year and respond by altering policy elements in the model according to specified rules. With this authority agent, the analysis would not specify a specific set of policy actions; rather, the analyst would specify (to the authority agent) the nature of the public agency responses to be simulated. For example, a rule about the way land will be released in response to demand levels and/or prices would be specified rather than the vector of the precise quantities of land released each year in each zone. This would allow the modelling system to be responsive to emerging results, similar to the situation in reality, and would allow it to also indicate the impacts of a more general strategic approach for a public authority in terms that would seem to be more readily appreciated by those involved.
Some questions arise regarding the potential addition of an ‘authority agent’: How are general policy rules rather than policy actions specified? How are the exceptions to general policy rules identified and handled, given that they do happen in reality and thus should be incorporated into the model simulation? More generally: is it possible to simulate the behaviour of a single authority agent as proposed here? Given the specific nature of transport system infrastructure changes, would it be more appropriate to include both general policy rules and specific policy actions together? And how should the split between general policy rules and specific policy actions be determined?

4. Conclusions

The overall intention in the work described here, and the essence of the questions posed above, is to identify better ways of providing a more complete representation of the full spatial economic system of an urban area. Implicit in this is the notion that an evaluation of the impacts of transport policy needs to include consideration of the impacts of transport policy on the full spatial economic system. This includes the impacts of the transport system on economic activity, on the evolution of the urban form and on the quality of life of its citizens along with the negative environmental impacts of the production of transport supply. An evaluation of the impacts of transport policy on not only the transport system, but also on the rest of the spatial economic system - along with the impacts of land use policy (as well as other economic policy elements) on the transport system - requires a more complete representation of this sort. When large components of the full system are not included, there is a risk that important impacts will be missed; at best, the analyst makes a judgement about whether this is happening and either makes an adjustment or provides a caveat.

The development and use of more complete representations of the full spatial economic system is ambitious - the development of improved methods for such representations even more so. The data requirements are extensive. The development effort is long and expensive. The resulting modelling system is often cumbersome, requiring long run times and powerful computing equipment, and not well understood by many of those seeking to use it for policy analysis.

One of the successful aspects of the work described here has been the combination of both practical and research components. It is very unlikely that sufficient support for this program of research concerning advanced modelling systems could have been obtained from research sources alone. What made it possible was the willingness of the State of Oregon Department of Transportation to allow the various components of the modelling system being developed on its behalf to be used as a platform for further research. But, in addition, the pressures of practical model development also encouraged an adherence to deadlines and a willingness to compromise in the development of a modelling system that could be used for research, which ensured that progress was made towards a range of larger goals – whereas a 'purer' research development program might have taken a path that involved a more comprehensive design process at the expense of adherence to a schedule.

The hope in the work described here is that the use of agent-based micro-simulation will result in more 'transparent' and ultimately more simple models that will more closely mimic actual agent behaviour and thus involve less computing effort. But many questions remain about the precise form of the behaviour of various kinds of agents in different contexts and how to appropriate incorporate representations of this behaviour into practical modelling systems.

Many of these questions, like the ones indicated here, at first can seem esoteric and far removed from any practical policy analysis work to be done. But they are not! They are now highly relevant to the wider modelling and analysis communities given the large potential and demonstrated practicality of agent-based micro-simulation. In fact, it is likely that many will have to be answered in order for the promise of agent-based micro-simulation methods to realise their potential. Such answers will be needed in order for these methods to beyond the current situation where various forms of 'aggregate model compromises', like the logit choice model applied to a 'typical agent', are being used and the resulting difficulties endured.

The focus here has been on behavioural questions. Of course, various other questions concerning the implementation of this sort of modelling system within a practical working environment have also arisen. The computing requirements are significant, and some questions have concerned the most appropriate approaches for distributing the effort among clusters of processors at different stages of a model run. Issues have arisen concerning the most effective ways to manage and present the vast quantity of results that are generated. Calibration is another big area of concern.

With regard to calibration in particular: Large agent-based micro-simulations of the sort being considered here include random elements, and thus do not provide the same results for the same inputs in a given model run. This is very different from the situation with aggregate, equilibrium-based systems – which always seek out the same equilibrium point given the same inputs. This has given rise to some questions related to the calibration process: Are the observed values obtained from the real world more like the equilibrium points provided by an aggregate, equilibrium-based system, or are they perhaps better viewed as one possible set of results similar to one set of results obtained from a given run of an agent-based micro-simulation system? Is there a set of 'expected' values that the real world is tending towards, which the observed values differ from because they are only one possible realisation of a distribution of possible values tending towards these 'expected' values? Are there 'random components' in real world values? Are we doing the right thing when we 'force' the results from an aggregate equilibrium-based model to exactly match observed values? How about for agent-based micro-simulation models: are we doing the right thing when we 'force' the results to exactly match observed values? In this work, the approach in calibration has tended to mimic the approach used in similar large agent-based micro-simulation work being done in other contexts. The behaviour of individual agents has been adjusted to match observations of actual individual behaviour to the extent such behaviour is known and/or observed, and then the aggregate emergent behaviour of the larger system is examined to see if it tends to follow general observed patterns and expectations. This general approach can sometimes be discomforting for those steeped in years of work calibrating aggregate models so that they reproduce aggregate observed values. Clearly, this approach relies heavily on the content of the modelling system at the level of the individual agent – which is why many of the questions about behaviour outlined above are so important.

Various questions have been identified; and some directions of investigation seeking some answers have been described. Yet much remains to be answered. It would seem to be an exciting time: the emerging practicality of agent-based micro-simulation techniques could be heralding a revolution in spatial economic modelling generally and transport system modelling in particular. But some key parts of the puzzle still need to be sorted out before things can really take off. And there are agencies willing to participate and provide support. All the parts seem to be in place for some exciting research and development.

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