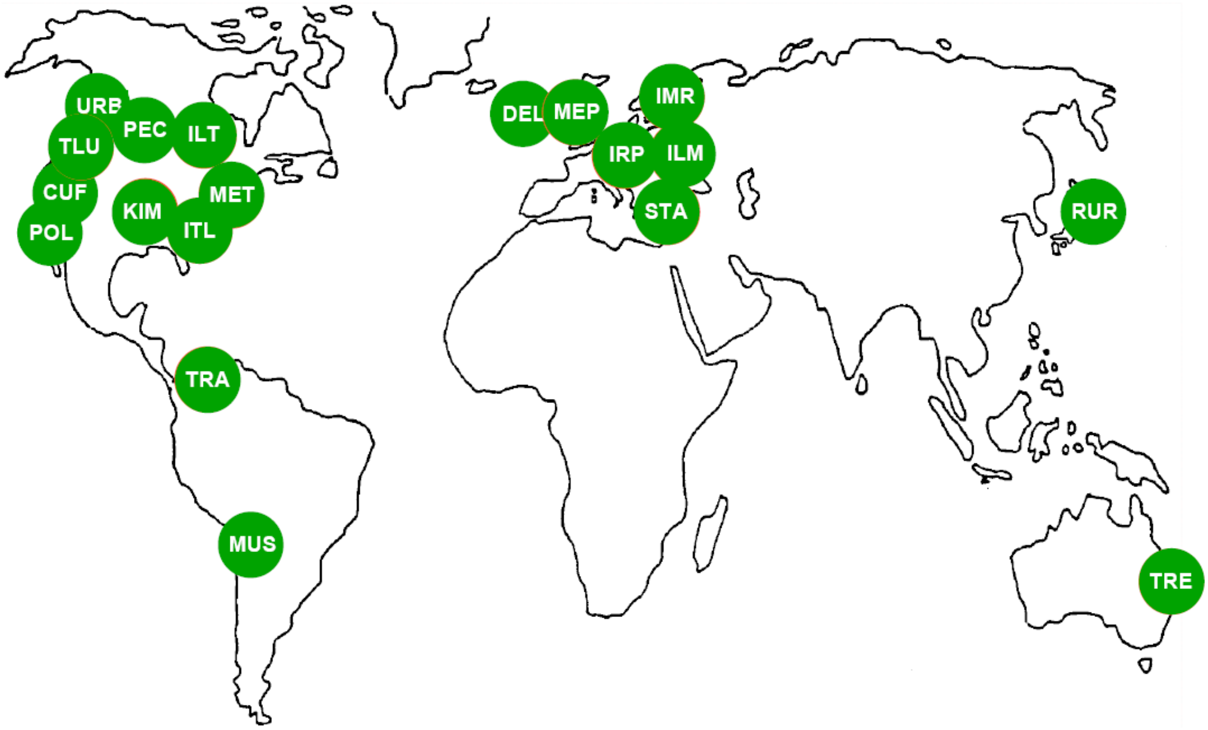

Work Package 2.5

Synthesis report on the state of the art on existing land use modelling software

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SustainCity

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SEVENTH FRAMEWORK PROGRAMME
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Synthesis report on the state of the art on existing land use modelling software

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10/05/2010

Abstract

The Sustain City project aims to develop innovative land-use transport interaction models for three major European metropolitan areas, namely Paris, Brussels, and Zurich. Those are based on the association of UrbanSim with dynamic traffic assignment models, METROPOLIS in the case of the Paris metropolitan area, MATSim for Brussels and Zurich. UrbanSim is an urban simulation software, which aims to simulate transformations in the two interacting systems that are transportation and land use, at the scale of a metropolitan area and over a long time span. This report reviews the main features of this software.

In parallel to the report written regarding the UrbanSim software, this report tries to shed light on the ILUTE and ILUMASS software. ILUTE is an urban simulation software aiming to simulate transformations in the two interacting systems that are transportation and land use, at the scale of a metropolitan area and over a long time span. ILUMASS aims at embedding a microscopic dynamic simulation model of urban traffic flows into a comprehensive model system incorporating both changes of land use and the resulting changes in transport demand. This report reviews the main features of both software models. It also contains an overview of other land-use models.

Keywords

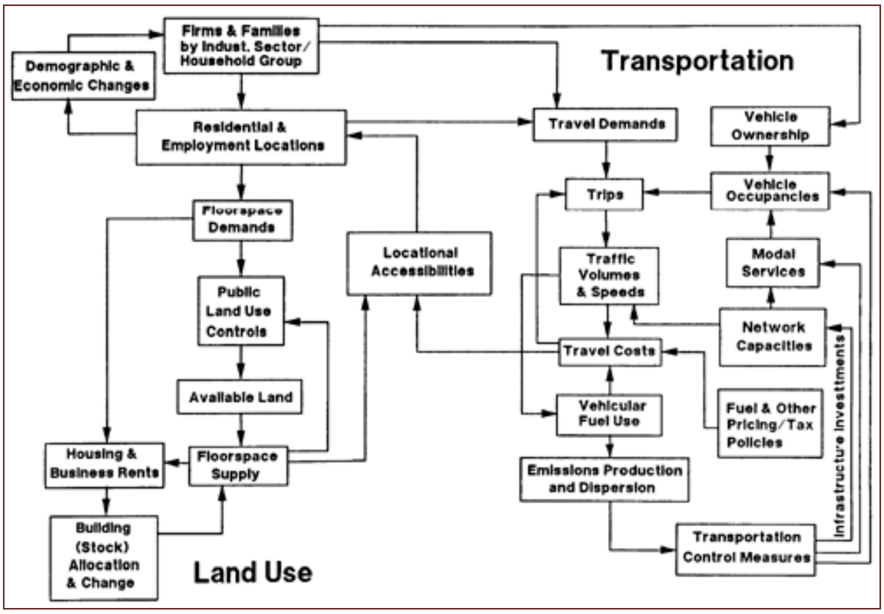
UrbanSim; ILUTE; ILUMASS; Geographical unit of analysis; Overview of land-use models; Software architecture

1 Overview of land-use models

Initially we present a review of operational integrated urban land use transportation models, that is, models that have been developed and applied in either a research or actual planning context within the recent years. The term Integrated implies a feedback mechanism of the type shown in Figure 1, between the transportation system and the rest of the urban land use system. Here the "land use" system supplies the transportation system with estimates of the location and volume of travel generators.

"Land use" is a general term here, covering both the types and intensities of activities taking place at specific urban sites as well as the physical area of land and any built structures used in support of such activities (Southworth, 1995). This involves modelling the demand for employment, residential, shopping, and other activities at different sites, and then translating and possibly constraining these demands based on appropriate physical or artificial (i.e., planner-imposed) land utilization rates. The more ambitious models also include the simulation of housing stocks and floor space requirements for industrial buildings. Within some models, this also means simulation of pricing effects on, in particular, residential choice. A further extension in a limited number of modelling systems is a linked simulation of demographic change, allowing the urban area's population to evolve along with the evolution of the physical city within which it lives and works.

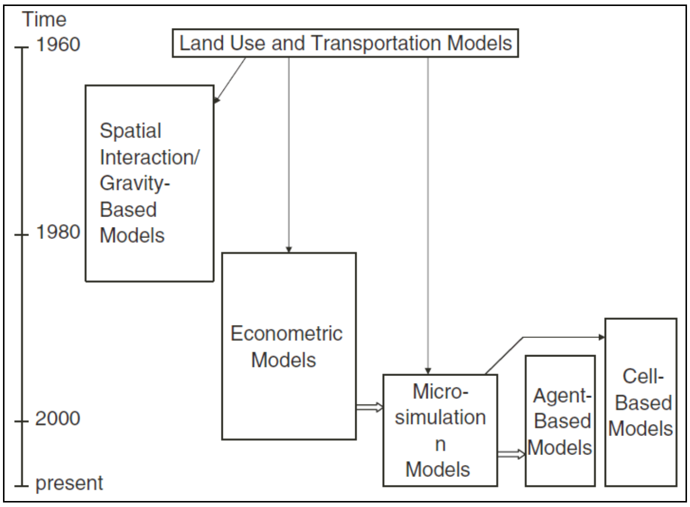
Figure 1 Interaction between land-use and transportation



Source: (Southworth, 1995)

Figure 2 shows the time trends of the last 50 years of development land use and transport models. This Figure describes the chronological development process of models and gives an approximate timeline for the adoption of various modelling frameworks within transportation and land use research.

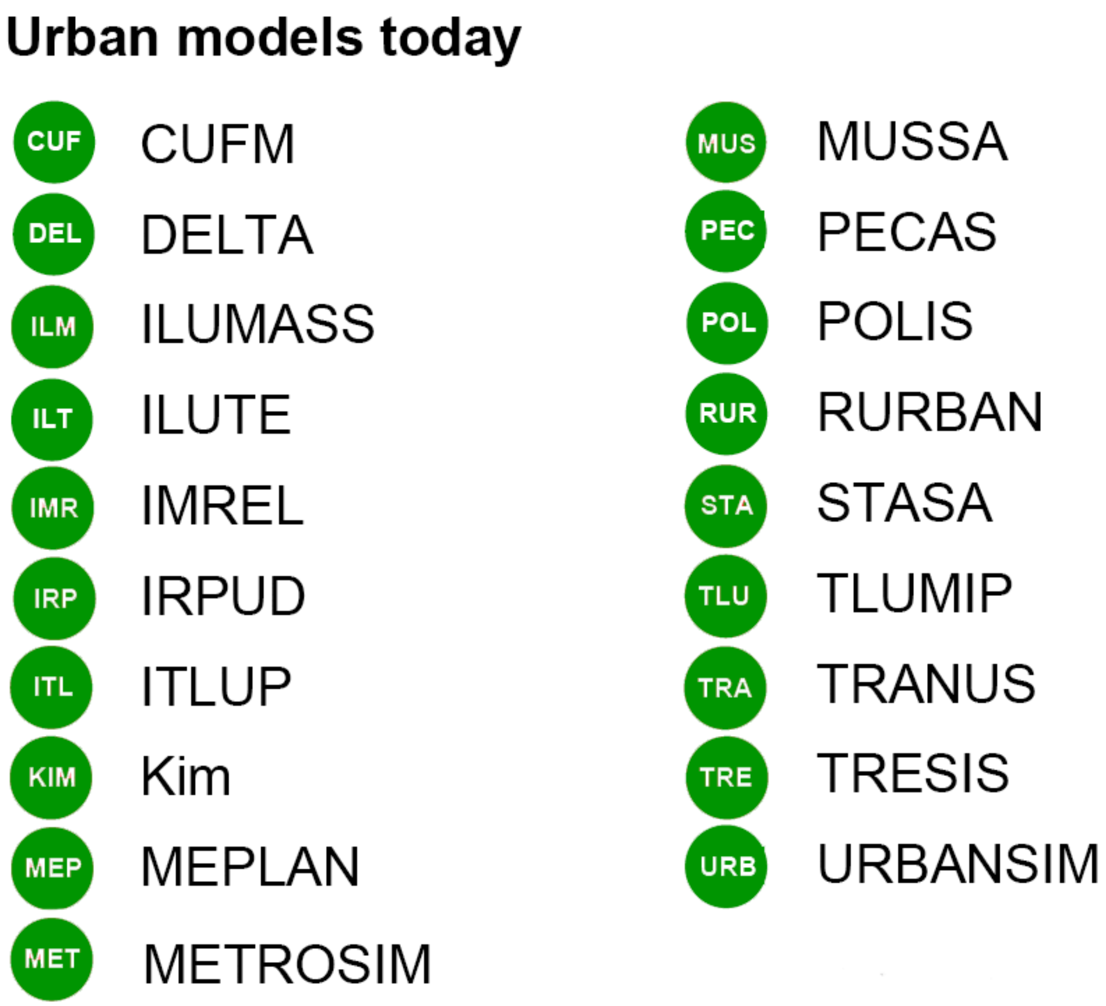
Figure 2 Chronological Development of Land Use and Transportation Models



Source: (Iacono, 2008)

To describe the current state of models developed, we rely on the work of (Wegener, 2004) and (Wegener, 2005) which analyzed and compared with 20 models including ILUTE and UrbanSim.

Figure 3 Integrated Land-Use Transport Models



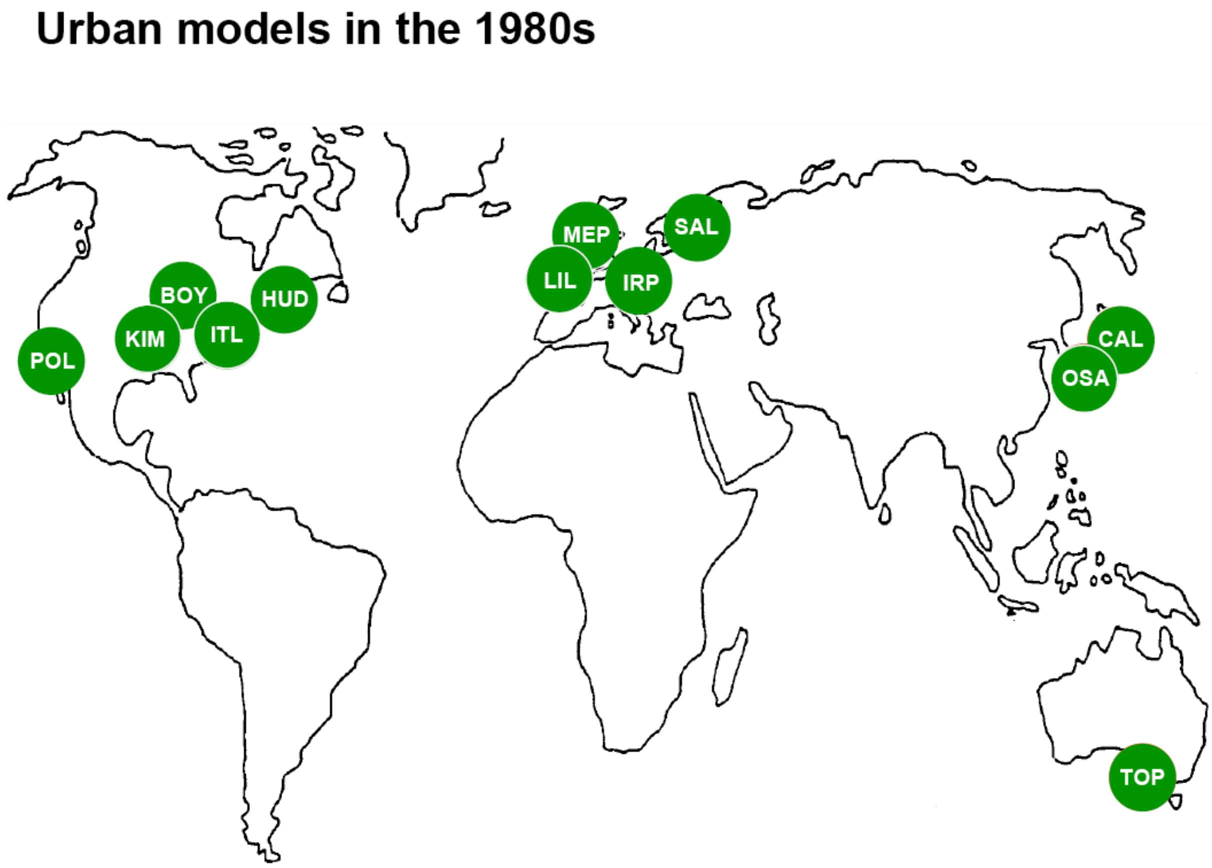
Adopted from Wegener 2005

Figure 4 and

Figure 5 show that the number of models has been multiplied by 2 in twenty years on the continents of North America and Europe.

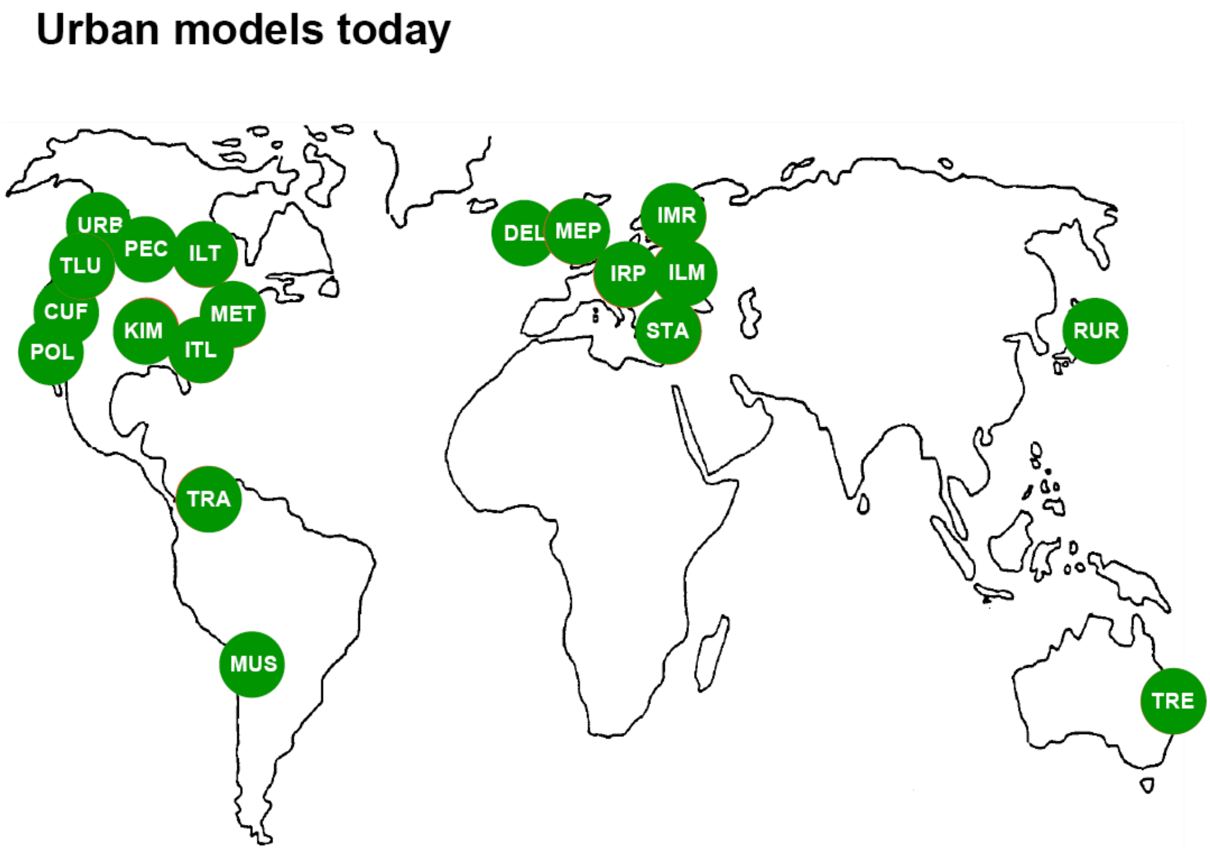
Figure 5 also shows that two models are currently deployed in South America (TRANUS and MUSSA).

Figure 4 Urban models in the 1980s



Adopted from Wegener 2005

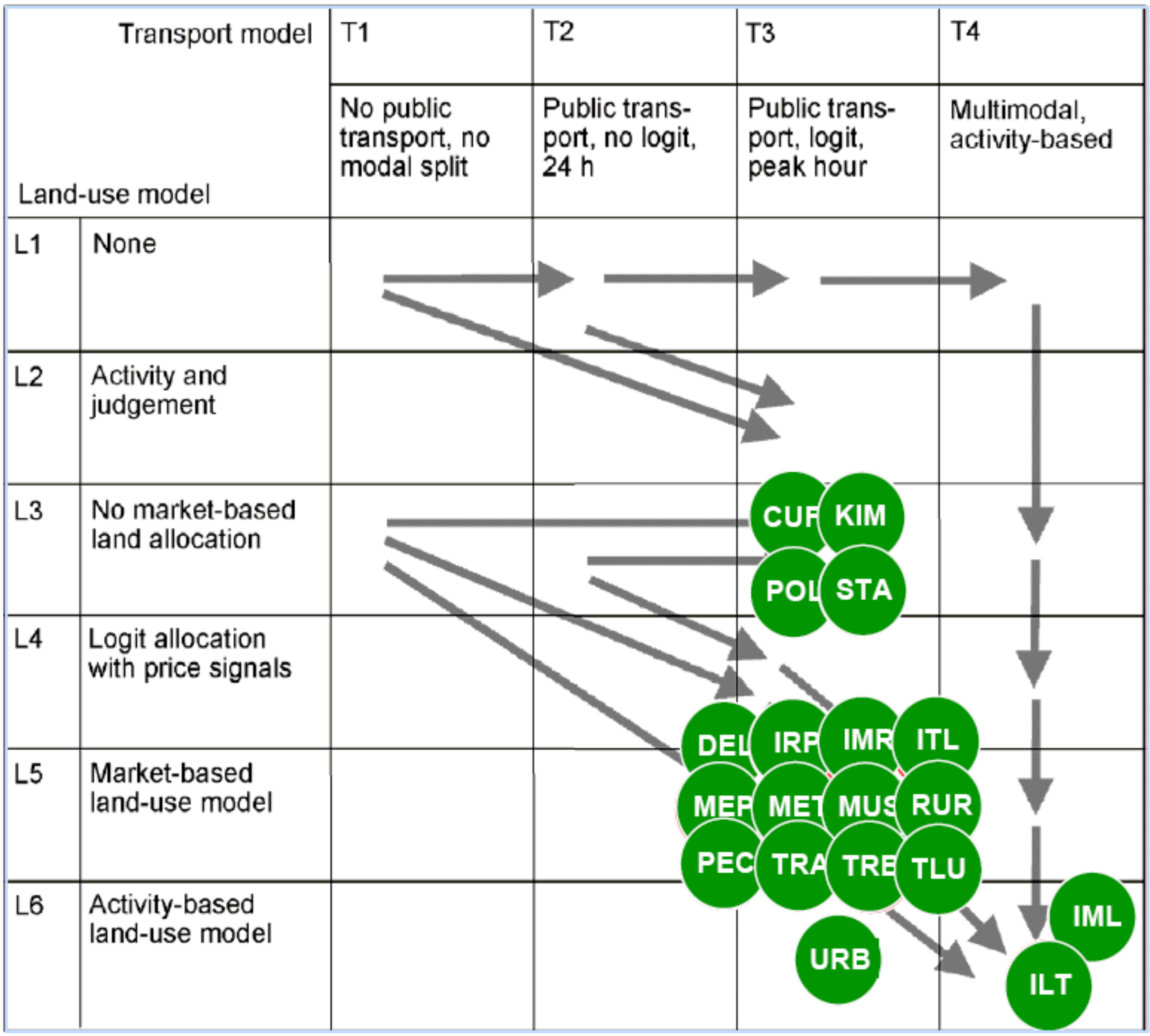
Figure 5 Urban models today



Adopted from Wegener 2005

Figure 6 shows the evolution of urban land-use and transport models. We can see that ILUTE and ILUMASS are the “most advanced” models in that classification, closely followed by UrbanSim. All three models are disaggregate, non-equilibrium, 1-year step frameworks (Hunt et al., 2005). Note that SustainCity will advance the transport modelling part of UrbanSim.

Figure 6 Evolution of urban land-use transport models



Adopted from Wegener 2005

1.1 Comprehensiveness

All twenty models are comprehensive in the sense that they address at least two of the eight subsystems identified below (see Table 1). Only ILUTE, MEPLAN, STASA, PECAS, TLUMIP and TRANUS encompass all eight subsystems. IRPUD, LILT, METROSIM and TRESIS address all subsystems except goods transport and KIM models goods movements but not physical stock and land use. Half of the models make no distinction between activities (population and employment) and physical stock (housing and workplaces). Six models (DELTA, CUFM, MUSSA, POLIS, RURBAN and URBANSIM) do not themselves model transport but rely on interaction with existing transport models. Only DELTA, ILUTE, IR-

PUD, LILT and URBANSIM model demographic change and household formation. Table 1 shows the urban subsystems that are modelled with each model.

1.2 Model structure

With respect to overall model structure, two groups can be distinguished. One group of models searches for a unifying principle for modelling and linking all subsystems; the others see the city as a hierarchical system of interconnected but structurally autonomous subsystems; the resulting model structure is either tightly integrated, 'all of one kind', or consists of loosely coupled sub models, each of which has its own independent internal structure. The former type of model is called 'unified', the latter 'composite'. Nine of the twenty models (BOYCE, MUSSA, KIM, MEPLAN, METROSIM, PECAS, RURBAN, TRANUS and STASA) belong to the unified category, the remaining eleven are composite. The distinction between unified and composite model designs has important implications for the modelling techniques applied and for the dynamic behaviour of the models (see Table 1).

Table 1 Urban subsystems represented in land-use transport models

Models	Speed of change							
	Very slow		Slow		Fast		Immediate	
	Networks	Land use	Work-places	Housing	Employ-ment	Popula-tion	Goods transport	Travel
BOYCE	+				+	+		+
CUFM	(+)	+	+	+	+	+		(+)
DELTA	(+)	+	+	+	+	+		(+)
ILUTE	+	+	+	+	+	+	+	+
IMREL	+	+	+	+	+	+		+
IRPUD	+	+	+	+	+	+		+
ITLUP	+	+			+	+		+
KIM	+				+	+	+	+
LILT	+	+	+	+	+	+		+
MEPLAN	+	+	+	+	+	+	+	+
METROSIM	+	+	+	+	+	+		+
MUSSA	(+)			+	+	+		(+)
PECAS	+	+	+	+	+	+	+	+
POLIS	(+)	+			+	+		(+)
RURBAN	(+)	+			+	+		(+)
STASA	+	+	+	+	+	+	+	+
TLUMIP	+	+	+	+	+	+	+	+
TRANUS	+	+	+	+	+	+	+	+
TRESIS	+	+	+	+	+	+		+
URBANSIM	(+)	+	+	+	+	+		(+)

(+) provided by linked transport model

Source: (Wegener, 2004)

1.3 Theoretical foundations

In terms of theoretical foundations, models can be distinguished by this classification:

- Eleven models (DELTA, IMREL, KIM, MEPLAN, METROSIM, MUSSA, PECAS, RURBAN, TLUMIP, TRANUS and TRESIS) represent the land (or floor space or housing) market with endogenous prices and market clearing in each period; three (ILUTE, IRPUD and URBANSIM) have endogenous land and housing prices with delayed price adjustment. These models are indebted to microeconomic theory, in particular to Alonso's (1964) theory of urban land markets or bid-rent theory. The models without market equilibrium rely on random utility maximisation; however, three of the microeconomic models (MUSSA, RURBAN and STASA) are hybrids between bid-rent and random utility theory. All models with transport sub models use random utility or entropy theory for modelling destination and mode choice, except the STASA model.

- Only KIM and METROSIM determine a general equilibrium of transport and location with endogenous prices. Other models are equilibrium models of transport only (ILUTE, IRPUD, ITLUP and TLUMIP), of transport and activity location separately (IMREL, MEPLAN, PECAS, TRESIS and TRANUS), or of transport and location combined but without endogenous prices (BOYCE and LILT). MUSSA equilibrium not only satisfies market clearing with demand and supply endogenously defined, but also equilibrates agents' interactions or location externalities to equilibrium. Five models apply concepts of locational surplus (IMREL, POLIS), random utility (DELTA, IRPUD and ITLUP) or profitability (CUFM) to locate activities. ITLUP may be brought to general equilibrium, but this is not normally done; METROSIM may produce a long-run equilibrium or converge to a steady state in annual increments. STASA describes the short-term redistribution of population during a day due to transport events.

- IMREL uses its equilibrium mechanism to determine the distribution of housing that maximises locational surplus and so is a true optimisation model, whereas all other models in the sample simulate one particular scenario only. Despite earlier attempts at optimisation in urban models, optimisation approaches in urban models have all but disappeared.

- Several other theoretical elements are built into some models. MEPLAN, METROSIM, PECAS and TRANUS use export base theory to link population and non-basic employment to exogenous forecasts of export industries. DELTA, ILUTE, IRPUD, LILT, TLUMIP and URBANSIM apply standard probabilistic concepts of cohort survival analysis in their demographic and household formation sub models. IRPUD also utilises ideas from time geography, such as time and money budgets, to determine action spaces of travellers in its transport sub model.

1.4 Modelling techniques

In all twenty models, the urban region is represented as a set of discrete sub areas or zones. Time is typically subdivided into discrete periods of one to five years. This classifies all models except IMREL (which is static) as recursive simulation models:

- STASA uses a one-year period for the urban/regional modelling and a one-hour period for redistribution effects due to transport events. In nine models (BOYCE, IMREL, KIM, LILT, MEPLAN, METROSIM, PECAS, RURBAN and TRANUS) transport and location are simultaneously determined in spatial-interaction location models in which activities are located as destinations of trips; in the remaining models (and in the employment location model of IMREL) transport influences location via accessibility indicators. In the models with network representation, state-of-the-art modelling techniques are applied, with network equilibrium the dominant trip assignment method despite its weakness of collapsing to all-or-nothing assignment in the absence of congestion. Only ITLUP, MEPLAN, STASA and TRANUS have multiple-path assignment allowing for route-choice dispersion, and only ILUTE and TLUMIP use activity-based trip generation.

- For representing flows of goods, spatial input-output methods are the standard method. DELTA, KIM, MEPLAN, PECAS and TRANUS use input-output coefficients or demand functions for intersectional flows and random utility or entropy models for their spatial distribution. MEPLAN, PECAS and TRANUS incorporate industries and households as consuming and producing 'factors' resulting in goods movements or travel.

- With the exception of CUFM, all models are aggregate at a meso level, i.e. all results are given for medium-sized zones and for aggregates of households and industries. CUFM, ILUTE and TLUMIP are disaggregate, i.e. apply micro simulation techniques. CUFM uses detailed land information in map form generated by a geographical information system. IRPUD starts with aggregate data but uses micro simulation in its housing market sub model; work is underway to make more sub models microscopic (Salomon et al., 2002). ILUTE and URBANSIM apply zones but use smaller spatial units such as grid cells or parcels in some sub models.

1.5 Dynamics

The discussion on dynamics is related to the issue of equilibrium (see above). Equilibrium models are based on the assumption that interdependent model variables, such as prices, supply and demand, adjust to equilibrium with zero delay or, if adjustment is delayed, equilibrium is eventually reached. Dynamic models, on the other hand, are based on the assumption that some changes, e.g. changes in demand, are faster than others, e.g. responses of supply, and that these differences in speed of adjustment are so large that urban systems are normally in disequilibrium. All but three (BOYCE, IMREL, KIM) of the twenty models are recursive simulation models. Recursive simulation models are called quasi-dynamic because, although they model the development of a city over time, within one simulation period they are in fact cross-sectional. This is however only true for strictly unified models. Composite models consist of several interlinked sub models that are processed sequentially or iteratively once or several times during a simulation period. This makes composite models well suited for taking account of time lags or delays due to the complex superposition of slow and fast processes of urban development. However, some models insufficiently use this feature, because their simulation period of five years has the effect of an implicit time lag – a too long time lag in most cases. This problem is likely to disappear as faster computers will make shorter simulation periods of one or two years more feasible.

1.6 Tabular overview of the model systems

This section contains a tabular overview of different model systems. It is mainly based on Timmermans (2003).

1.6.1 Lowry-Garin Model

Main purpose	
Type	
Generation1	Aggregate spatial interaction-based model
Programming language	
License	
Comprehensiveness	Population, employment, housing, workplace, travel
Model structure	
Software components	• Economic base sub model • Spatial allocation sub model
Theoretical foundation	Gravity-based model
Travel model	
Features	Considered to be the first transportation / land use model (1964)
Developer	See Lowry (1963, 1964)
Case studies	Pittsburgh region

[1] "Generation" refers to the modelling generation according to Timmermans (2007). Alternatives are "Aggregate spatial interaction-based models", "Multinomial logit-based models of utility-maximizing actors", and "Towards activity-based microsimulation models".

1.6.2 IRPUD Model

Main purpose	This model simulates employment change by industrial sector and demographic changes within a set of labour market regions.
Type	Partially Micro simulation Model
Generation	Aggregate spatial interaction-based model / Micro simulation
Programming language	
License	
Comprehensiveness	Population, employment, housing, workplace, travel, land use
Model structure	Loosely coupled sub models
Software components	Interlinked sub models: • Transport • Ageing • Public programs • Private construction • Labour market • Housing market To model: • Aging of people • Households • Dwellings and workplaces • Relocation of firms • Redundancies an new jobs • Non-residential construction and demolition • Residential construction • Rehabilitation and demolition • Changes of jobs • Changes in residence • Car ownership and transport
Theoretical foundation	Travel: Doubly constrained and production-constrained entropy-maximizing model Land use: Markov process Different model scopes: • (Macro analytical) economic model • (Macro analytical) demographic model • (Mesoscopic) spatial model • (Micro analytical) land use model
Travel model	Integrated
Features	Typical for the first generation: use of gravity models Typical for the latest generation: use of micro simulation
Developer	See Wegener (1982, 1983)
Case studies	Dortmund region

1.6.3 ILUTE Model

Main purpose	Evolution of an entire urban region with emphasis on transport. Schedules individuals' activity-travel patterns within a household context.
Type	Agent Based
Generation	Activity-based, micro simulation model
Programming language	C++
License	
Comprehensiveness	Population, employment, housing, workplace, travel, land use, environment
Model structure	Loosely coupled sub models
Software components	• Interrelated behavioural core components: o Land development o Location choice o Activity / travel o Auto ownership • Demographics • Regional economics • Government policies • Transport system • Flows, times, and so on • External impacts
Theoretical foundation	Rule based: reducing number of choices / logit model for selecting best option. Modelling methods to capture object behaviour: State transition models, random utility models, rule-based (computational) models, learning models, exploration models, and newly developed hybrids of these approaches
Travel model	Integrated, agent-based
Features	Integration of environment sub model Model differentiates between persons and household, and between firms (modelled as agents) Buildings are recognized in addition to zones Spatial units: zones, grid cells, parcels ILUTE status: on going research
Developer	See Salvini et al. (2005) and Miller, E. J. (2009)
Case studies	Greater Toronto and Hamilton Area

1.6.4 MEPLAN Model

Main purpose	Simulate the effects of urban policies
Type	Spatial Input-Output Model
Generation	Utility-maximizing multinomial logit-based model
Programming language	
License	Commercial
Comprehensiveness	Population, employment, housing, workplace, travel, land use
Model structure	Loosely coupled sub models
Software components	• Land use/economic module (LUS) • Transportation module (TAS) • Economic evaluation module (EVAL) An interface program called FRED couples these modules.
Theoretical foundation	Input-output model: predict the change in demand for space Random utility concepts: spatial system, transport model
Travel model	Integrated, 4 stage transport model
Features	
Developer	See Echenique (1977, 1994) and Echenique et al. (1969, 1980, 1990, 1995)
Case studies	Santiago, Chile, Sao Paulo, Teheran, Bilbao, Nepal's

1.6.5 TRANUS Model

Main purpose	Simulate and evaluate transportation, economics, and/or environmental Policies
Type	Spatial Input-Output Model
Generation	Utility-maximizing multinomial logit-based model
Programming language	
License	Creative Commons License
Comprehensiveness	Population, employment, housing, workplace, travel, land use
Model structure	Tightly integrated sub models
Software components	• Land use / activities model • Transport model
Theoretical foundation	• Land use: spatial input-output model • Transport model: logit model for mode choice, utility functions estimate generalized costs Discrete choice approach: Components of the urban/regional and transport system, from trip generation to mode choice, path choice, location choice, land use choice, and others
Travel model	Integrated, also models goods transport
Features	Download available: http://www.modelistica.com/download.htm
Developer	See De la Barra (1989)
Case studies	Applied in a large number of cities in Latin America, USA, Europe (e.g. Brussels) and Japan

1.6.6 CUF-2 Model

Main purpose	Simulate urban growth and development policies, scenarios for future development
Type	Cellular automata
Generation	Utility-maximizing multinomial logit-based model
Programming language	
License	
Comprehensiveness	Population, employment, housing, workplace, land use
Model structure	Loosely coupled sub models
Software components	Probability of land use change: • The first sub model computes the development of undeveloped sites • The second sub model models previously developed sites
Theoretical foundation	Land use models: multinomial logit-based models Spatial sub model: allocation rule based
Travel model	External
Features	In contrast to other models: • CUF-2 projects population from the 'bottom-up' (projects population growth at the city/sub area level and then aggregates upwards) • CUF-2 allocates growth to individual sites (according to their potential)
Developer	See Landis (1994)
Case studies	California

1.6.7 MUSSA & RURBAN Model

Main purpose	Predicts the location of households and firms and the resulting rents
Type	
Generation	Utility-maximizing multinomial logit-based model
Programming language	
License	
Comprehensiveness	Population, employment, housing
Model structure	Tightly integrated sub models
Software components	
Theoretical foundation	RURBAN: Random Utility/Discrete Choice Model
Travel model	External
Features	Spatial allocation of land uses by bid function
Developer	Martínez (1992, 1997)
Case studies	Santiago City

1.6.8 METROSIM Model

Main purpose	Designed to study the relationship between land use and transport
Type	
Generation	Utility-maximizing multinomial logit-based model
Programming language	
License	Proprietary software
Comprehensiveness	Population, employment, housing, workplace, travel, land use
Model structure	Tightly integrated sub models
Software components	Contains sub models for: • Basic industry • Non basic industry • Residential and commercial real estate • Vacant land • Households • Commuting and non commuting travel • Traffic assignment
Theoretical foundation	METROSIM: Random Utility/Discrete Choice Model Mode choice: multinomial logit model
Travel model	Integrated
Features	
Developer	See Anas (1982, 1983)
Case studies	Chicago Area

1.6.9 DELTA Model

Main purpose	Designed to interact with a transportation model to forecast land use changes
Type	Spatial Input-Output Model
Generation	Utility-maximizing multinomial logit-based model
Programming language	
License	Licensing is on a project specific basis and includes the services of the model developer
Comprehensiveness	Population, employment, housing, workplace, land use
Model structure	Loosely coupled sub models
Software components	Urban part of DELTA contains sub models for: • Development process • Demographic change (e.g., household formation) • Economic growth • Location and relocation of households and jobs in the property market • Car ownership choices • Changes in employment status and commuting patterns • Changes in the quality of residential areas Moreover the regional part of DELTA contains sub models for: • Migration between different urban areas • Location of investment/disinvestment • Production and trade
Theoretical foundation	Land use model input from external transport model: Types of accessibility and area quality
Travel model	External
Features	
Developer	See Simmonds (2001) and Simmonds et al. (1998)
Case studies	

1.6.10 UrbanSim Model

Main purpose	UrbanSim is a model for integrated planning and analysis of urban development, incorporating the interactions between land use, transportation, and public policy
Type	Agent based
Generation	Utility-maximizing multinomial logit-based model
Programming language	Python
License	GNU General Public Licence
Comprehensiveness	Population, employment, housing, workplace, land use
Model structure	Loosely coupled sub models
Software components	• Macroeconomic Model (extern) • Travel Demand Model (extern) • Transition Model (Demographic and Econometric) • Relocation Model • Location Choice Model • Real Estate Development Model • Real Estate Price Model
Theoretical foundation	UrbanSim: discrete choice model based on the random utility theory Household and Employment Mobility Model: multinomial logit model
Travel model	External, delivers accessibility measures
Features	• Spatial units: zones, grid cells, parcels • Transportation model models: car, walk and bicycle • Disaggregated presentation of agents (household, jobs) • Aim: Open up the model and the process of its design as much as possible (in longer terms: interact with the model via the internet). • Allows to include own variables
Developer	See Waddell (2000, 2002) and Waddell et al. (2003, 2004, 2007, 2008)
Case studies	Detroit, Durham (North Carolina), Eugene-Springfield, Honolulu, Houston, Phoenix, Salt Lake City, San Antonio, San Francisco, and Seattle/Washington (Puget Sound region)

1.6.11 IMREL Model

Main purpose	
Type	
Generation	Utility-maximizing multinomial logit-based model
Programming language	
License	
Comprehensiveness	Population, employment, housing, workplace, travel, land use
Model structure	Loosely coupled sub models
Software components	This list may be incomplete: • Employment location • Residential location
Theoretical foundation	• Total number of household and workplaces exogenously given • Location of workplaces and transport system are given (normative) • Allocation of working force to zones: multinomial logit-based model → model finds location of predefined number of housing units (utility maximization)
Travel model	Integrated
Features	In contrast to other models IRMEL is a: • Static simulation model • Normative model on residential location
Developer	See Anderstig and Mattsson (1991, 1992, 1998) and Boyce and Mattson (1999)
Case studies	Stockholm region

1.6.12 Ramblas Model

Main purpose	Intended and unintended consequences of planning decisions related to land use, building programmes, and road construction for households and firms
Type	
Generation	Activity-based, micro simulation model
Programming language	Fortran
License	
Comprehensiveness	Population, employment, housing, workplace, travel, land use
Model structure	
Software components	
Theoretical foundation	Rule based
Travel model	
Features	
Developer	See Veldhuisen et al. (2000)
Case studies	Eindhoven region

1.6.13 ILUMASS Model

Main purpose	Dynamic simulation model with a focus on urban traffic flows, including activity behaviour, changes in land use, and effects on environment
Type	Agent Based
Generation	Activity-based, micro simulation model
Programming language	Some Modules are implemented in Java, uses geographic information system (GIS) technology
License	
Comprehensiveness	Population, employment, housing, workplace, travel, land use, environment
Model structure	
Software components	Modules: • Land use • Transport • Environment To model: • Changes in land use • Activity patterns and travel demand • Traffic flows • Goods transport • Environmental impacts of transportation and land use
Theoretical foundation	Markov Logit, Monte Carlo
Travel model	Integrated, goods transport and travel, microscopic model
Features	The land-use component of ILUMASS based on IRPUD (see above), but uses the microscopic version (of IRPUD). Integration of environment module
Developer	Beckmann et al. (2007)
Case studies	Dortmund region

1.7 Conclusion

The Sustain City project is focused on the UrbanSim Software. For that reason, this review is focused on UrbanSim itself, as well as on alternative modelling systems, with the intention to identify useful elements that might also be introduced into UrbanSim.

Except for UrbanSim itself, only two of the presented urban land-use transport models are disaggregated and agent-based. These are ILUTE and ILUMASS. Many similarities between UrbanSim, ILUTE, and ILUMASS can be recognized: e.g. the representation of the land (or floor space or housing) market and the modelling of demographic changes. The following sections summarize the most important aspects of ILUTE (section 2), ILUMASS (section 3) and UrbanSim (section 4).

2 ILUTE

2.1 Starting with ILUTE

The ILUTE (Integrated Land Use, Transportation and Environment) research program since the 90s – a collaboration of several Canadian universities, including the University of Toronto (Miller et al.) – seeks to develop an integrated transportation and land use model. This integrated model of micro simulation of urban systems encompasses four components (urban development, choice of location, activity/travel, and vehicle ownership) and seeks to forecast their reactions and interactions subsequent to the implementation of various urban policies relevant to land management and government interventions affecting transportation and the environment.

ILUTE simulates the activities of individual objects (agents) as they evolve over time. These objects include persons (with households and families), transportation networks (road and transit networks), the built environment (houses and commercial buildings), firms, the economy (interest rates and inflation), and the job market. The simulator evolves the state of the urban system from a specified base month to a specified target month.

The model simulates the temporal and spatial activities of demographic and economic agents as they change gradually from a specified base month (or year) to a specified target month (or year). The software is produced to predict the evolution of an urban area over future horizon (for example 10–20–30 future years).

In ILUTE, a major emphasis has been placed on market demand-supply interactions especially in residential and commercial real estate markets. This software is such an integrated full-feedback model that allows a multilevel decision framework, where longer-term decisions influence the shorter-term decisions with full-feedback opportunity (Salvini & Miller, 2005).

The ILUTE model is a dynamic urban modelling system works based on the disaggregated nature of the elements playing the main role in the evolution of an integrated urban structure. It attempts to describe the behaviour of the agents and its changes over an extended period of time and its possible location throughout the analyzed region based on no imposed equilibrium assumptions. It is completely Object Oriented consider the full population of the region of the study.

2.2 Main modules

2.2.1 Different sub-models

The goal of the ILUTE is to provide software for travel demand modellers to experiment with dynamic micro simulation sub-models of urban land development, location choice processes and travel behaviour. The framework for the ILUTE project contains a sample set of sub-models of several short run and long run dynamic events.

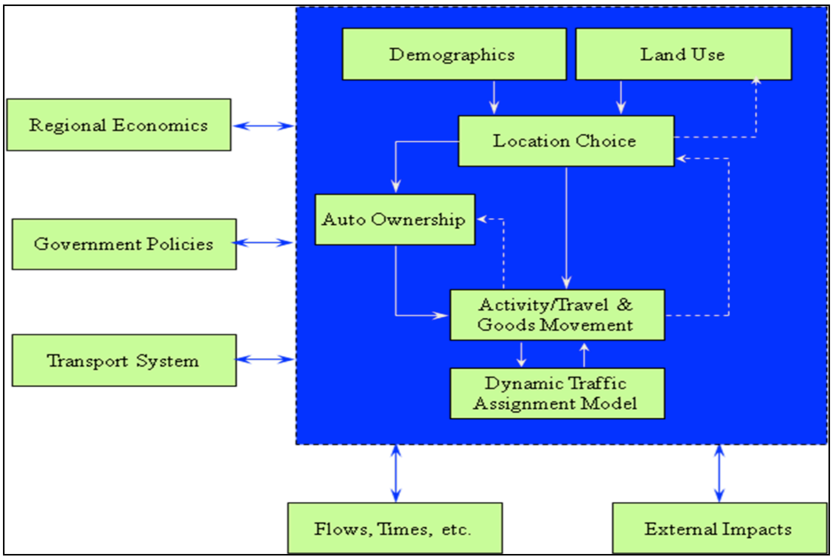
The various sub-modules that comprise ILUTE are:

- Housing Market Sub-model (determines if and where a household will move)
- Auto Transactions Sub-model (determines if a household will buy/sell/trade an auto)
- Activity Sub-model (generates activities in time and space for each person)
- Demographic Sub-model (manages births, deaths, in and out migration, marriage, etc.)
- Output Sub-model (presentation of results)

The approach of ILUTE as presented in Figure 7 is two-fold:

- Micro simulates households' residential choice and activity-travel behaviour.
- Use a hybrid approach of firms' location choice micro simulation and aggregate regional economics.

Figure 7 ILUTE core model



Source: (Miller, 2009)

The core of ILUTE is a simulation framework that allows different sub-models to be plugged into it. The core keeps track of the state of the simulated world and all the objects in it. It also provides supporting tools that can synthesize objects to create an initial world and save the state of the world to a database.

The ILUTE software supports the followings capabilities (Ghauche, 2010):

- Synthesize a test set of households, persons, jobs, dwelling units, and buildings,
- Import spatial data (census tracts, Transportation Tomorrow Survey (TTS) planning districts, TTS traffic zones), transit and road networks, travel time data (by mode and time of day), and text-based economic data (interest rates and consumer price indices),
- Evolve the state of the system to an arbitrary date using an arbitrary time step by simulating the activities and behaviours of individual objects (e.g. persons and households),
- Track (display) the activities and behaviours of individual objects in the system as they evolve,
- Simulate population in-migration and out-migration,
- Export spatiotemporal data for visualization in 3D (static or animated),
- Read and write state information to a relational database.

2.2.2 How does it work: Theoretical foundation

ILUTE is largely based on autonomous agent theory (Miller, 2009). The population is simulated (as persons, households and decision making units), which then has processes simulated based on the current attributes of the agent, using "probabilistic state 'transition' models". ILUTE uses several different types of models for "triggering processes", or "sudden transitions from a passive to an active state at an arbitrary point in time".

A variety of modelling methods are employed within ILUTE to capture object behaviours (Salvini & Miller, 2005):

- State transition models,
- Random utility models,
- Rule-based (computational) models,
- Learning models,
- Exploration models,
- And newly developed hybrids of these approaches.

2.2.3 Architecture

ILUTE object structure

The list of classes below provides some insight into the current architecture of ILUTE (Salvini & Miller, 2005).

- Architectural Classes:
  - Application (the parent class of the software)
  - Database Administrator (reads and writes the system state to disk)
  - World (the simulated system)
- Agents:
  - Persons (each individual person is modelled by the system)
  - Households (a set of persons who live in the same dwelling unit)
  - Firms, Establishments (represents the decision-making of a company)
  - Property Owner
- Physical Classes:
  - Transportation Network (multi-modal network consisting of Nodes and Links)

- Travel Times (by mode: e.g. walk, bike, auto, transit, etc.)
- Vehicles
- Buildings, Dwelling Units
- Location (a geographic point), Neighbourhood (a boundary with common traits)
- Planning Districts (a prototypical "higher level" spatial boundary)
- Monetary Values (capture monetary values as a date-value pair: e.g. $1.00 in 1986)
- Schedule

• Sub-models:

- Housing Market Sub-model (determines if and where a household will move)
- Auto Transactions Sub-model (determines if a household will buy/sell/trade an auto)
- Activity Sub-model (generates activities in time and space for each person)
- Output Sub-model
- Demographic Sub-model (manages births, deaths, in and out migration, marriage, etc.)

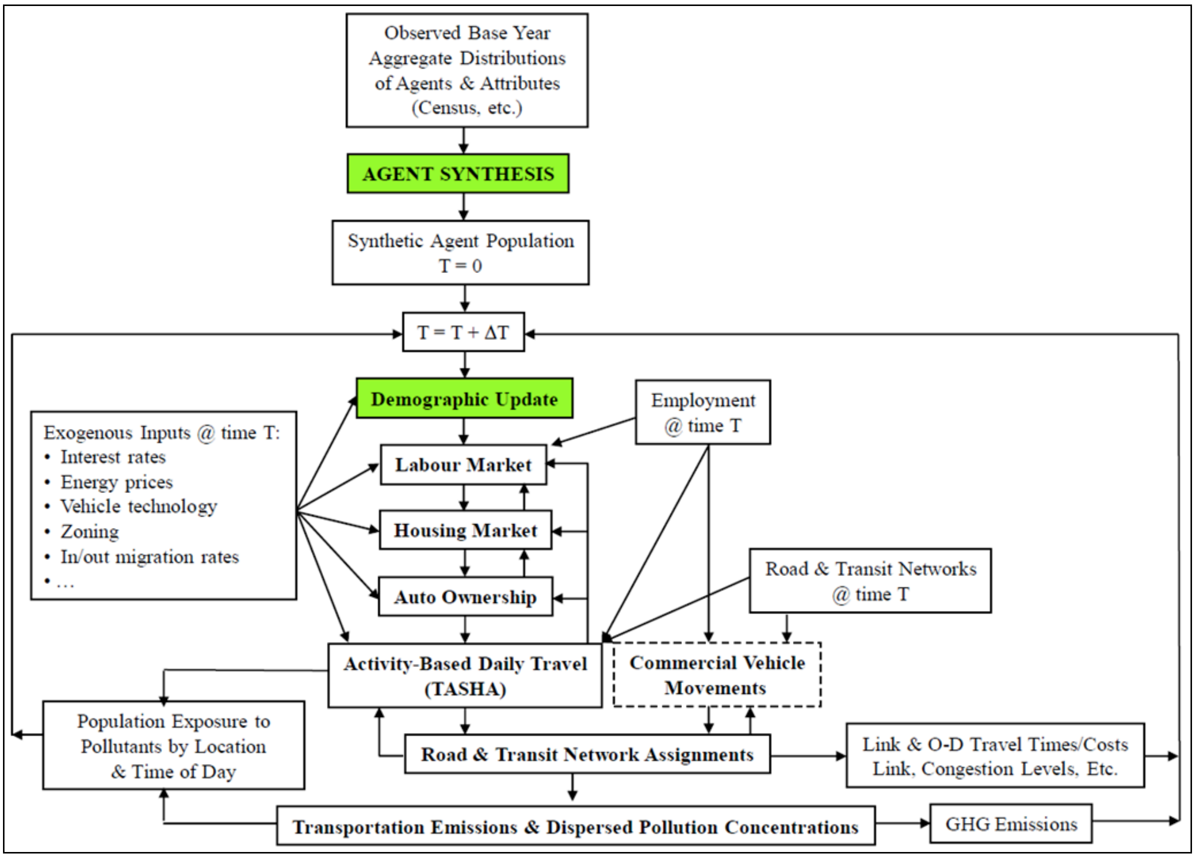
• Supporting Classes:

- Bid (a financial bid on a transaction)
- Job
- Market Pools (track participation in the marriage and housing markets)
- Market Moderators (process transactions within a given market)
- Simulated Object (anything updated over time)
- Simulation Date (current date/time of the simulation)
- Spatial Object (anything with a Location)
- Stressors (things that cause stress to agents: e.g. travel time, financial problems)
- Stress Manager (tracks, manages, and resolves "stress" in the life of the agents)
- Temporal Data Manager (manages time-varying data sets)

ILUTE model structure and processing

Figure 8 shows the simulation process of a future horizon (T + ΔT) from a reference horizon (T).

Figure 8 ILUTE model structure



Source: (Miller, 2009)

The procedure "Agent Synthesis" in the model allows to analyze and to synthesize socio-economic data (Census…) of the reference year. This procedure consists of four sequential phases: the synthesis of households and persons, the synthesis of buildings and dwelling units, the assignment of households to dwelling units, and the assignment of the primary work mode.

For the simulation horizon, the following sub-models are executed serially:

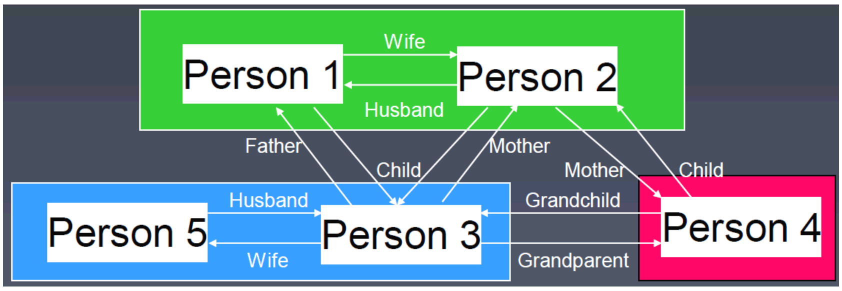
- Demographic Update
- Labour Market
- Housing Market
- Auto Ownership
- Activity-based Daily Travel (TASHA)

As shown in Figure 9, each sub-model uses external data (employment, road and transit networks…) on the target horizon.

Representation of Persons, Households, and Families

One of the key features of the ILUTE is the explicit representation of persons, households, and families. The inclusion of the family relationship within ILUTE enables a number of insightful decisions to be made in location choice and activity scheduling. Family relationships captured within the ILUTE include mother, father, spouse, ex-spouses, children, and siblings. Figure 9 shows an example of family relationships where we can distinguish five persons, three households and two families (Miller, 2009).

Figure 9 Example family relationships



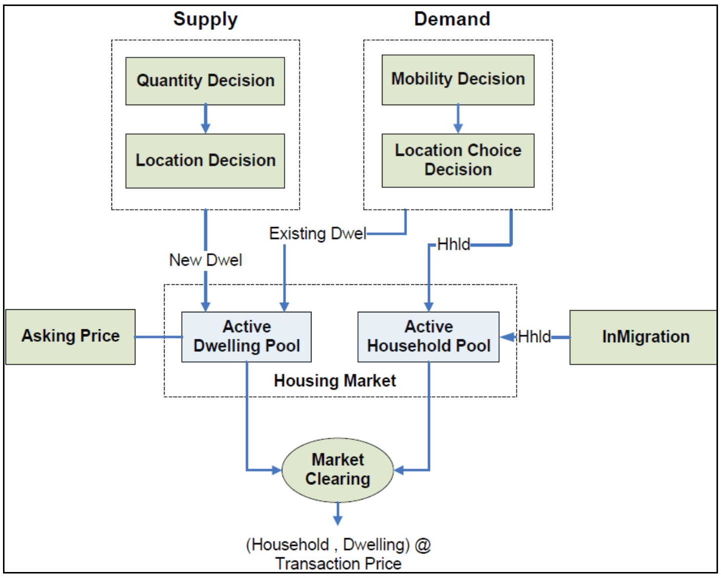
Source: (Miller, 2009)

Behaviour and Decision-Making

In ILUTE, objects called decision-making units implement behaviour. ILUTE's explicit representation of compound groups like households and families means that decisions can be made directly by these objects. In other cases, several objects will collaborate to form ad-hoc decision-making units (for example, the drivers in a household may collaborate to make a decision about a vehicle purchase). The assignment or attribution of behaviours to collective decision-making units is a fundamental design feature of the ILUTE model. This feature delivers several practical benefits, including the ability to trace decisions on a per-entity basis and the ability to support multiple temporal decision scales. Some decision-making units are abstractions of real-world entities. A firm, for example, is an object within ILUTE that makes decisions. While in the real-world, it is persons in the firm that are actually making these decisions, the use of such objects as surrogate decision-makers is a useful and understandable abstraction of the real-world process (Salvini & Miller, 2005).

Figure 10 shows the sub-model used by ILUTE to simulate a housing market demand, supply and market equilibrium.

Figure 10 Housing Market micro simulation Model



Source: (Miller, 2009)

In ILUTE the Market Clearing process used is based on:

- Micro simulation clearing process (Dwellings cleared individually and not by type or any other level of aggregation)
- Auction based
- No equilibrium assumption
- Endogenous price-formation
- Location choice probabilities of bidding households, used to clear the market

TASHA

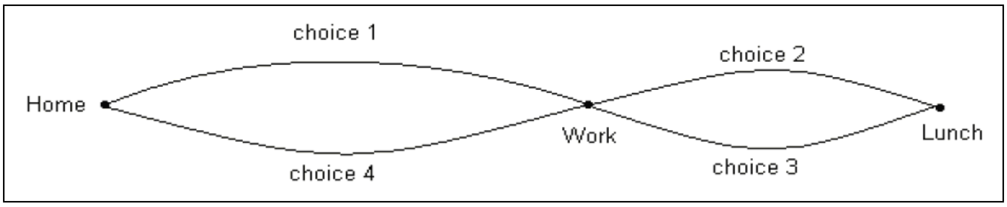
TASHA (Travel/Activity Scheduler for Household Agents) is activity scheduler model used in the ILUTE. This model generates activities in time and space for each person.

The main features of TASHA are:

- Generates all the movements of individuals
- Modal choice model based on the towers (See Figure 11)

• Resource allocation based on the utility of direct modes

Figure 11 Example a trip generated by TASHA



Source: (Dalibor, 2007)

TASHA is a rule-based model that builds on the concept of activity projects and schedules activities sequentially to predict an individual's daily schedule (See Figure 12). Briefly stated, a project is a collection of activity episodes that combine to achieve one goal (i.e. a "dinner at home" project involves the activity episodes of shopping, cooking, eating and cleaning among others). TASHA micro simulates the behaviour of every individual by going through the steps outlined below as shown in Figure 13 (Ghauche, 2010):

Step 1:

Within TASHA, all individuals have a pre-specified set of projects (e.g. work, school, shopping, in-home activities). At the onset of every day, the model selects random activity episodes (e.g. type, timing, duration and location) based on the frequency of this episode in an observed sample. This agenda constitutes the pool of activities that are likely to be done each day.

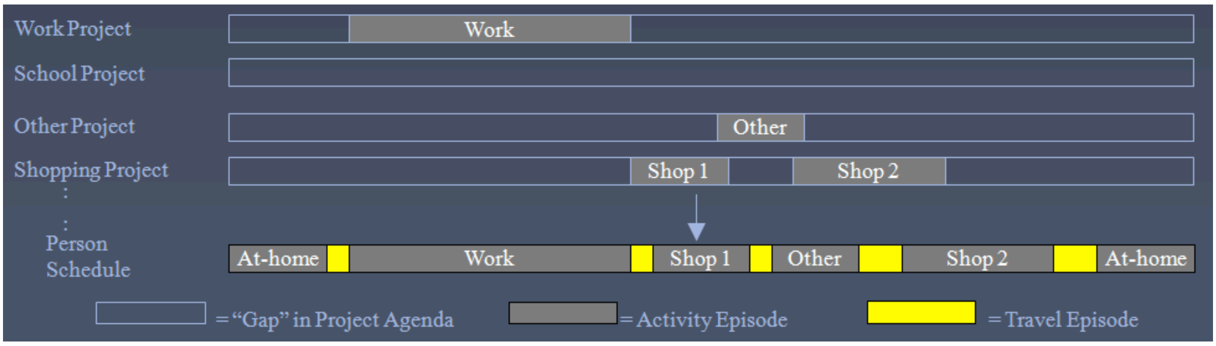
Step 2:

These episodes are sequentially "scheduled" using a set of rules according to a pre-specified priority order while making sure that spatio-temporal constraints are respected.

Step 3:

Associated with each activity episode is a travel episode that may or may not materialize depending on the location of the sequential activities. The scheduling of a travel episode includes a mode choice model given the household's vehicle resources and situational constraints (e.g. if an individual left home without a car to go to work, he may not use his car for work-based trip during the day).

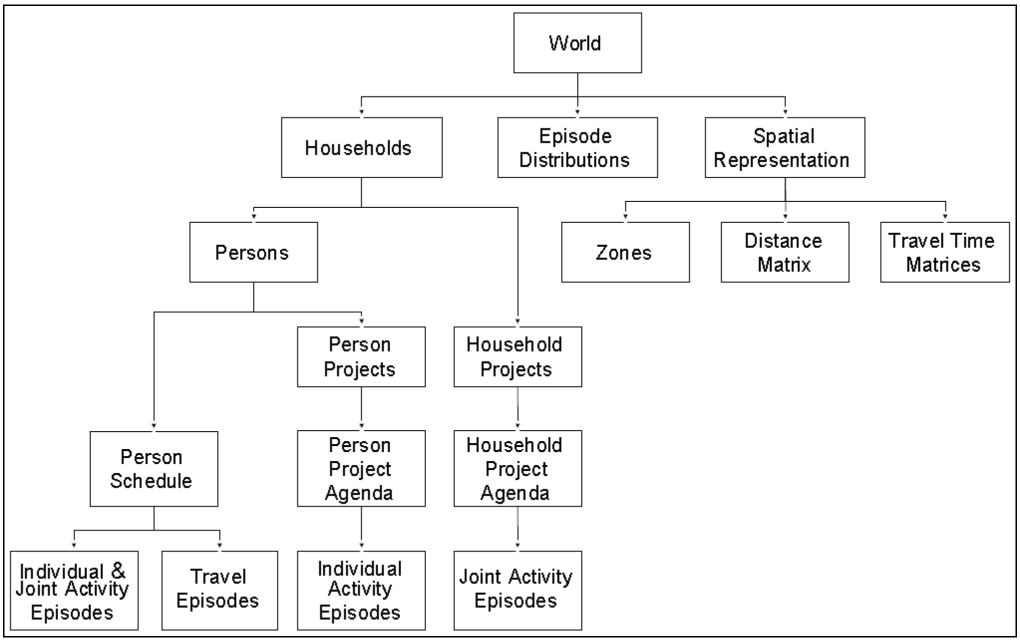
Figure 12 Scheduling Activity Episodes into a Daily Schedule



Source: (Miller, 2009)

TASHA captures intra-household interactions in two ways: In case of vehicle allocation conflict between two individuals, the car is allocated to a person to maximize the additive utilities of these two household members. By creating an ad hoc household decision making unit (Salvini & Miller, 2005) that has its own set of activity projects such as childcare and home-maintenance, TASHA adds the activity episodes within these pools to the pool of potential activities for each individual.

Figure 13 TASHA Structure



Source: (Miller & Roorda, 2003)

2.3 Dynamic process and fixed point

One contrast between the ILUTE approach to route choice and some of the more detailed ‘‘traffic’’ micro simulations, is that ILUTE adopts a conventional view regarding how individual travellers respond to congestion. Travellers are assumed to know, from past experience, the congested travel conditions on various links, and they make travel choices consistent with this knowledge. Thus, the route choice decisions of travellers are assumed to be in some sort of Wardrop equilibrium with the route choices of other travellers (Miller et al., 2004).

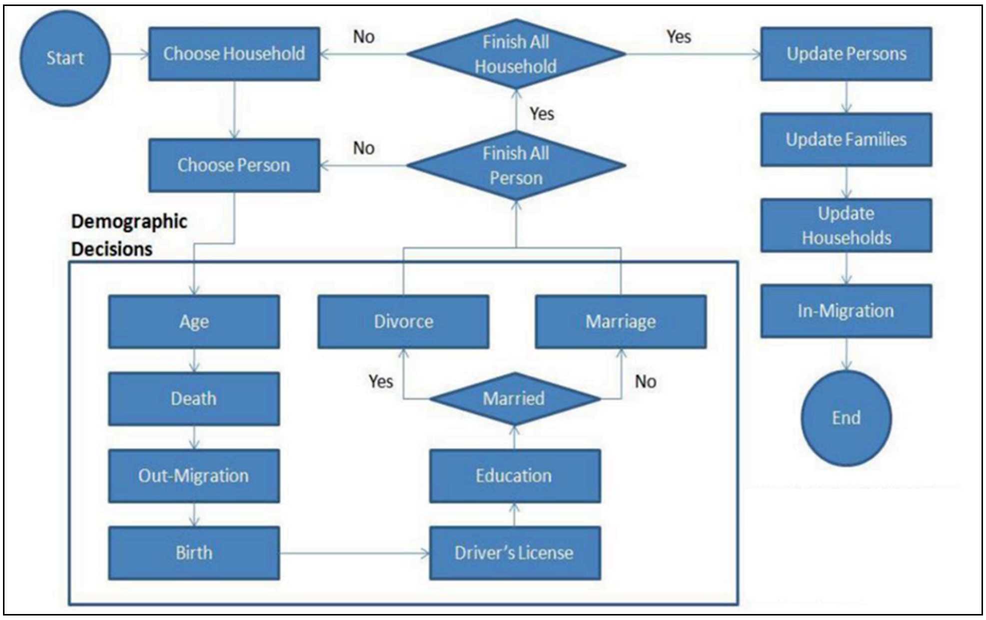
2.4 Interaction with demographic and transportation models

2.4.1 Interaction with demographic model

In addition to Census demographic data, time-series information on births, deaths, marriages and divorces have been assembled from provincial and federal sources to support the development of demographic sub-models dealing with the ''updating'' of the resident population (births and deaths) and household formation/ dissolution (marriages and divorces). Something, which has not yet been acquired in sufficient detail by the ILUTE team, is information on in- and out-migration from the GTA. Migration, however, is extremely important in a high-growth region such as Toronto and may prove to be a relatively problematic issue with which to deal.

A demographic updating procedure has been developed for the GTA that updates household, family & person attributes each year in a simulation run (see Figure 14).

Figure 14 Model of demographic updating in ILUTE



Source: (Miller, 2009)

The Household class in ILUTE performs the simulation of the behaviour of the household agents. Seemingly, the person class does the simulation of the person agent. The first step for simulating the agents in ILUTE is proceeded by the simulation of individuals, households, businesses and establishments. Each agent has variety of degree of freedom by which it can make decisions for which it is responsible. Figure 14 demonstrates the procedure of demographic decisions and the demographic updating mechanism within the ILUTE.

2.4.2 Interaction with transportation model

The current prototype does not include an explicit model of the transportation network. Rather, it assumes that such a model exists external to ILUTE that is able to provide travel times and costs by mode to ILUTE as required (currently zone-to-zone matrices are assumed to exist, but other representations are possible). The ILUTE architecture, however, has been designed to accommodate an integrated transportation network model (Salvini & Miller, 2005).

To the case study of Toronto ILUTE was connected with EMME/2 road & transit network assignment model -link speeds & volumes by hour of day- (Miller, 2009).

But a project started in 2004 aims to link the model ILUTE (and TASHA) the traffic model MATSIM to take into account the dynamics of traffic that does not as a static model EMME/2. The goal was to add new traffic simulator and activity generator sub-models to ILUTE. The current activity generator and traffic simulator (MATSIM) are overly simple and need to be replaced to provide more realistic simulation (Thibault, 2004).

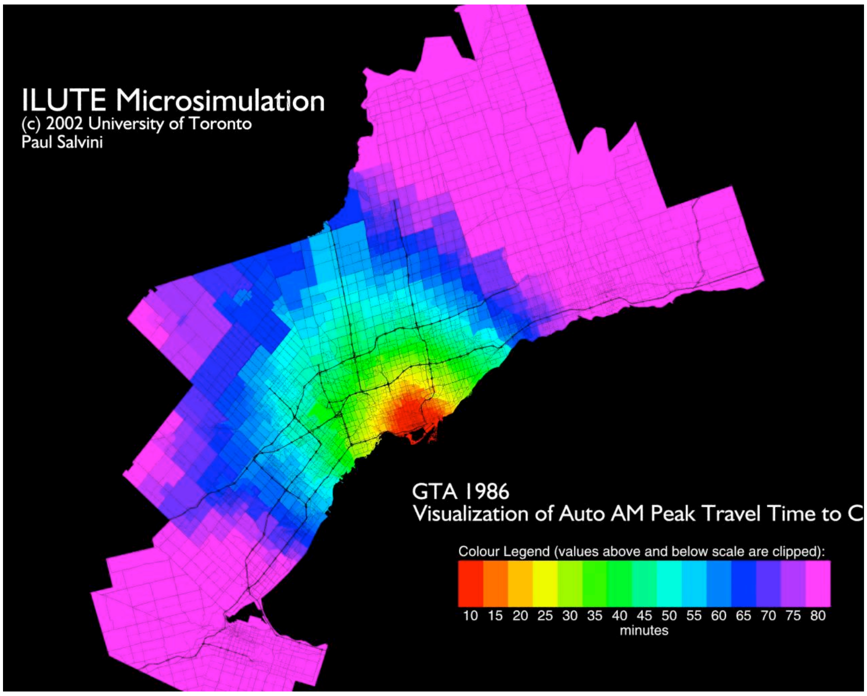
One contrast between the ILUTE approach to route choice and some of the more detailed ‘‘traffic’’ micro-simulations is that ILUTE adopts a conventional view regarding how individual travellers respond to congestion. Travellers are assumed to know, from past experience, the congested travel conditions on various links, and they make travel choices consistent with this knowledge (Miller et al., 2004).

2.5 Case studies

Greater Toronto and Hamilton Area (GTHA)

- 1.1 million households,
- 1.0 million families,
- 3.3 million persons.

Figure 15 Example of ILUTE output - Time access to the centre of Toronto



Source: (Miller, 2009)

The model was extensively validated with respect to its base year of 1996 and for a forecast year of 2001. Overall, the model was found to perform very well in both the base and forecast cases. It is deemed ready to be used in operational policy analyses for the GTHA.

2.6 Strengths and weaknesses of ILUTE

To identify weaknesses and strengths of the model ILUTE we rely on the comparison of the six urban models (including ILUTE) carried out research of Ghauche (2010).

2.6.1 Strengths

Strengths in the **scope** of ILUTE:

- Includes mobile energy and emissions
- Includes land use modifications
- Includes ecological processes
- Includes environmental indicators of sustainability
- Includes economic indicators of sustainability
- Includes social indicators of sustainability

Strengths in the **modelling approach** of ILUTE:

- Use Bottom-up approach
- Includes households
- Includes individual activities
- High spatial resolution (can handle multiple spatial aggregations)
- Takes into account a full day (24hrs)

Strengths in the **modelling techniques** of ILUTE:

- Use rule-based models
- Includes inter-individual interactions
- Includes ecological processes

2.6.2 Weaknesses

Weaknesses in the **scope** of ILUTE:

- Does not include stationary energy
- Does not include impact of environment on transport

Weaknesses in the **modelling approach** of ILUTE:

- Does not include firms
- Does not include activities of firms

Weaknesses in the **modelling techniques** of ILUTE:

- Does not use utility-based models
- Does not include intra-individual dynamics
- Does not include partnerships and competition between firms

3 ILUMASS

The objective of ILUMASS project (Integrated Land-Use Modelling and Transportation System Simulation) was to implement a fully microscopic model of urban land use, transport, and environment. With these objectives, ILUMASS is the only European counterpart to the growing number of large North-American modelling projects, such as ILUTE (Strauch et al., 2005).

ILUMASS was under development between 2002 and 2006 as an interdisciplinary joint research project. The project made considerable progress in the state-of-the-art in integrated urban models but run out of funding before it met its goals.

The following information is largely based on Strauch et al. (2005), often verbatim. In the interest of readability, the passages are not marked as quotations in most cases.

3.1 Starting with ILUMASS

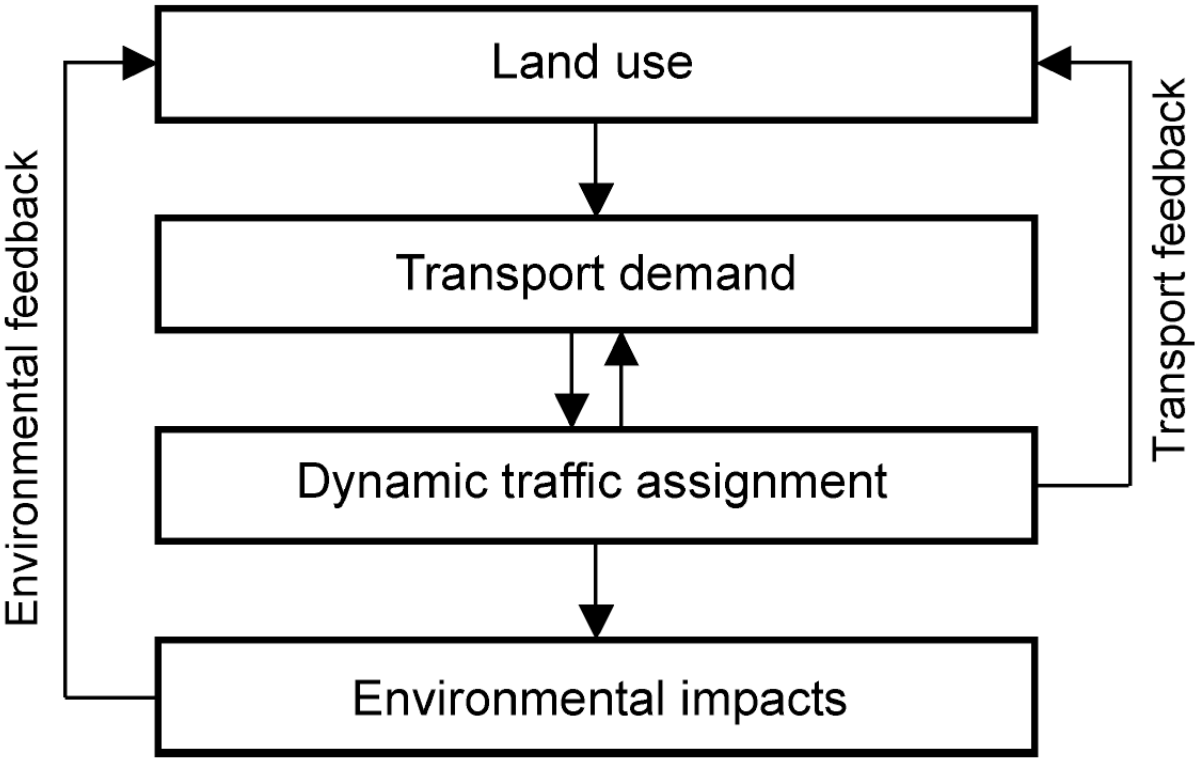
The ILUMASS model (Integrated Land-Use Modelling and Transportation System Simulation) is a disaggregated, microscopic model. The project aims at embedding a microscopic dynamic simulation model of urban traffic flows into a comprehensive model system that incorporates changes of land use, the resulting changes in activity behaviour and in transport demand, and the environmental impacts of transport and land use. Therefore, ILUMASS integrates three modules to a complete modelling system to provide a balanced view of the entire urban planning process: land-use, transport and environment (LTE). A detailed description of these models is given in the next section 3.2.

Each of these modules consists of several loosely coupled microscopic sub models. Every sub model has its own independent internal structure. A dedicated software component organizes the interplay of the different modules. They include models of demographic development, household formation, firm lifecycles, residential and non-residential construction, labour mobility in the regional labour market and household mobility in the regional housing market (Strauch et al., 2005).

“The ILUMASS project has two main highlights'” (Ghauche, 2010). First, ILUMASS is one of the first urban models that distinguish between households and firms. ILUMASS handles them as two different types of agents interacting in the urban context. This approach allows a more individual and effective approach in the model system. While most firms are interested in having good traffic connections, many households wish to live in detached single-family houses in pleasant natural environments, which is the reason for suburbanisation and urban sprawl (Wagner & Wegener, 2007).

The latter highlight considers a two-way feedback link between the land-use, transportation and environment (see Figure 16). There are two important kinds of feedback: The accessibility provided to locations in the region by the transport system influences the location decisions of developers, firms, and households. Firms and households also take environmental factors, such as clean air and absence of traffic noise, in location decisions into account.

Figure 16 Feedbacks in LTE models.



Source: (Strauch et al., 2005)

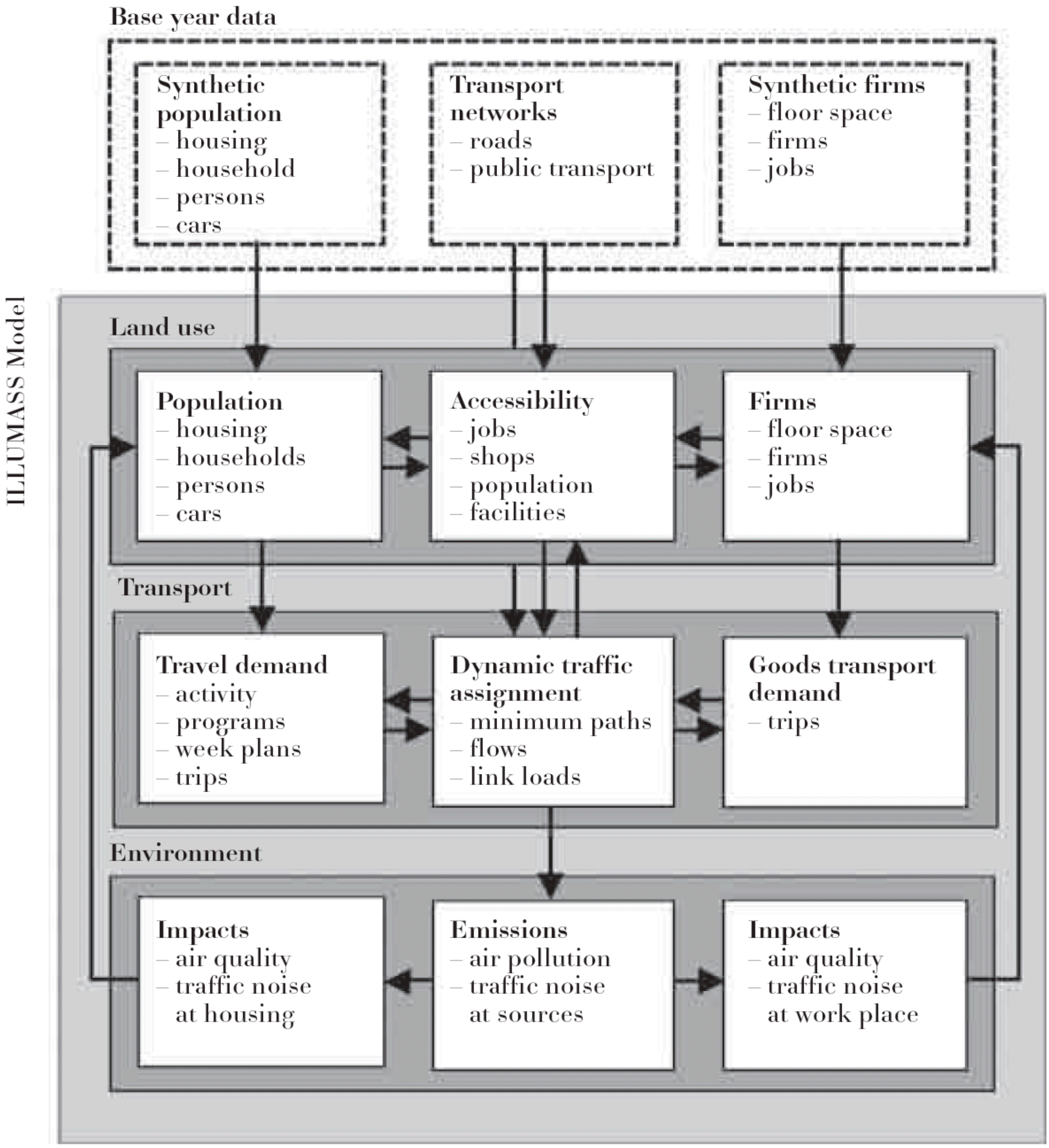
To meet the challenge in planning sustainable land use, transport and environment an interdisciplinary consortium of German research institutions conducted LUMASS. The consortium consists of the German Aerospace Center (DLR) in Berlin, the Institute of Spatial Planning at the University of Dortmund (IRPUD) together with Spiekermann & Wegener Urban and Regional Research (S&W), the Institute of Urban and Transport Planning at the RWTH

Aachen University (ISB), the Institute of Theoretical Psychology at the University of Bamberg (IfTP), the Centre of Applied Computer Science at the University of Cologne (ZAIK) and the Institute of Sustainable Infrastructure Planning at the University of Wuppertal (LUIS) under the coordination of DLR. (Strauch et al., 2005)

3.2 Module Overview

As mentioned above the ILUMASS model is divided into three modules: land-use, transport and environment (see Figure 17). Each of these modules consists of several microscopic sub models:

Figure 17 Modules and sub modules of ILUMASS.



Source: (Wagner & Wegener, 2007)

3.2.1 Land-use

The land use component of ILUMASS is based on existing land use parts developed at the Institute of Spatial Planning of the University of Dortmund (IRPUD). The macroscopic models of the IRPUD are re-implemented in microscopic form for ILUMASS. The microscopic land use sub modules include the following most important components (Wagner & Wegener, 2007):

- Population: The population model models the demographic lifecycle of persons and households such as people get older as time progresses, they have a certain probability to die, depending on their age and sex, new persons are born, couples move together or split up and young people move together and establish non-standard households. In addition, changes in employment are modelled.
- Firms: In analogy to the demography model of persons and households the simulation of firm lifecycle, called firmographie, models foundation, growth and eventual relocation, decline and closure of firms. These events are modelled by transition probabilities subject to exogenously provided economic structural change and business cycles.
- Residential mobility: The residential mobility sub model models location and housing decisions of households that move into, out of or within the region. Moves are modelled as transactions of households and landlords on the regional housing market. The attractiveness of a dwelling for a household is a weighted aggregate of the attractiveness of its location, quality and rent or price in relation to the household's housing budget. A household accepts a new dwelling if it promises a significant improvement in housing satisfaction. Otherwise, it continues its search annually until it finds suitable dwelling or abandons the search.
- Firm location/relocation: In analogy to the residential mobility sub model, this sub model simulates location or relocation decisions of firms. Firms dissatisfied with their present location examine up to ten alternative locations with respect to accessibility, size, price, quality and image and select a location if it offers a significant improvement of location satisfaction. Otherwise, the firm keeps its present location and may start a new search in the subsequent year.
- Residential buildings: The residential development sub model simulates investment decisions of private developers to demolish, upgrade or build residential buildings for rent or sale as a function of supply and demand on the housing market and profitability expectations. If the developer believes that positive returns can be achieved by upgrading or new construction, investments projects are planned. For each project, a zone and a micro location (raster cell, see section 3.3 for detailed overview about spatial data) are selected from the land zoned for residential use selected from the land zoned for residential use location criteria, such as accessibility, neighbourhood facilities, environmental quality and land price. The projects are executed in the implementation phase.
- Non-residential buildings: The model of non residential development examines the demand for floor space in each zone and develops new floor space in zones in which the vacancy rate is low. Floor space development is constrained by land use

restrictions in the municipal land use plans. Within a zone, micro locations (raster cells) close to existing firms are developed before isolated locations. Newly developed land is immediately designated as built-up land, but the new floor space is only offered on the market one year later, in order to consider construction time.

3.2.2 Transport

The transport part of ILUMASS models the demand for travel between different parts of the city at different times of the day and the demand for freight travel, as well as the resulting traffic flows based on state-of-the-art models of household activity patterns and the resulting mobility behaviour of individual household members.

The transport module consists of four different programs organised in three sub modules:

- Travel demand: The first and most complex one is a psychological actor model (activity generation model). Based on socio-demographic data of each person, it computes a weekly activity plan by considering 29 different activities grouped in four main groups such as personal, job and school, social activities and leisure. In addition, it takes the needs and wishes of people into account to replicate and forecast time dependent origin-destination matrices (O-D-matrices) for every hour of the day. These O-D-matrices are used as input into the dynamic traffic assignment sub module.

  An individual plan contains a sequence of activities and whether such an activity is located at home or not, these places are called opportunities. In the latter case, a trip to a place where this activity can be performed is needed. The travel demand sub model selects the place, the travel mode and the departure time. The travel demand module needs considerable computing time, e.g. the time to compute one activity time takes one second. For the whole study area (see section 3.5), it takes about two weeks.

  To partly overcome the difficulty with the long computing times needed by the psychological actor model, a more traditional demand generation algorithm has been included in a later stage of the ILUMASS project. Different from traditional models, it uses a very disaggregated approach to a compute 24 hourly origin-destination matrices for the study area.
- Dynamic traffic assignment: In the next step the route is computed by a microscopic dynamic traffic assignment, that iterates a shortest-path computation for the whole population in the study area (see 3.5) with a subsequent microscopic simulation until equilibrium has been reached. The resulting travel times are then used in the demand module and the additional traffic information, such as flows and speeds. The traffic information is used as input for the environment module.
- Goods transport demand: The demand generation for good transport was generated by a model that uses macroscopic data (input-output matrix of the German economy), together with a recent German survey on goods transport, to assign goods flow between the different companies in the city. The generated demand was used as additional input into the microscopic simulation above.

3.2.3 Environment

The environment module calculates the impacts of traffic forecasts and land use on the environment such as CO2 emissions, the distribution of air pollution, traffic noise, boundary layer effects (smog) and the barrier effects of traffic. The sub models apply state-of-the-art emission, air quality and noise propagation techniques based on the smallest spatial unit (see also 3.3) in ILUMASS defined by a grid of 352 000 grid cells of 100 x 100 m size. The environmental impact of traffic by vehicle category (lorry, car, bus), volume and speed are calculated as trajectories over a full week. The calculated environmental impact is then fed back to the land use module; there they influence the location choices of land use agents because they affect the quality of locations. This closes the iteration loop of ILUMASS.

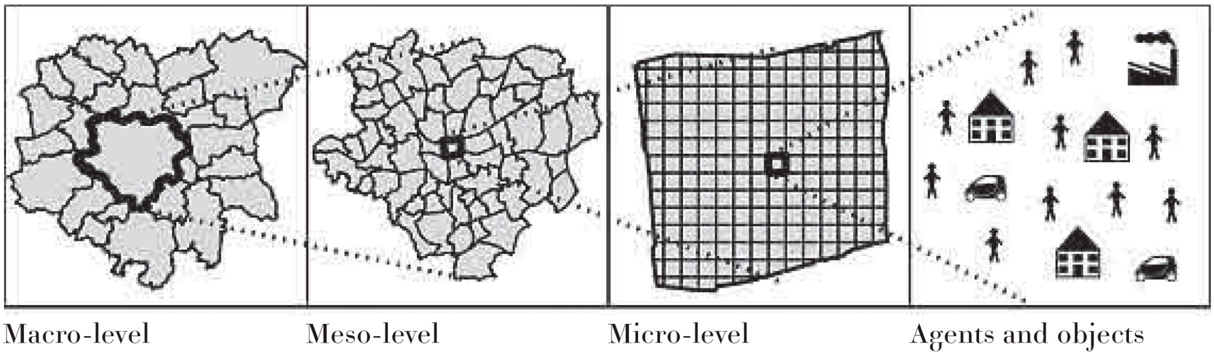
3.3 Data

The microscopic urban land-use, transport and environment models in ILUMASS use very detailed land-use, socio-economic and transport data and high-quality spatial data.

"In ILUMASS, three levels of disaggregation can be distinguished" (Wagner & Wegener, 2007): micro, meso and macro (see Figure 18). A grid cell of a 100 by 100 m size defines the smallest spatial unit. The whole study area is divided into 352 000 of such cells. These raster cells are used to locate agents and other objects such as firms, houses or other destination activities. The size of grid cells is a result of a trade-off between high disaggregate spatial scale and practicability reasons such as computing time.

The other two levels define traffic analysis zones for additional demand generation (meso) and municipalities in the Dortmund urban region (macro). In order to bridge the data gap between zones and raster cells, geographic information system (GIS) based techniques are used to disaggregate zonal data to raster cells (Strauch et al., 2005).

Figure 18 Macro-, meso- and micro-spatial resolution.



Source: (Schwarze et al. 2004)

ILUMASS uses data management to handle spatial data. The data management distinguishes static and dynamic data. Static, not modelled data already exist before the start of the simulation, e.g. the road networks, land use plans, factors that describe human behaviour and the various emission factors. Over the course of the simulation, dynamic data changes because the simulation itself generates it. The changes are important for the feedback between the simulation modules. Results that are relevant for later analysis are aggregated and stored. A dedicated software component organizes the interplay of the different modules (see Figure 19). This allows a “loose coupling” (Wegener, 2005) between the modules, in that each module is a self-standing executable and ILUMASS uses data management to handle spatial data. The data management distinguishes static and dynamic data. Static, not modelled data already exist before the start of the simulation, e.g. the road networks, land use plans, factors that describe human behaviour and the various emission factors. Over the course of the simulation, dynamic data changes because the simulation itself generates it. The changes are important for the feedback between the simulation modules. Results that are relevant for later analysis are aggregated and stored. A dedicated software component organizes the interplay of the different modules (see Figure 19). This allows a “loose coupling” (Wegener, 2005) between the modules, in that each module is a self-standing executable and interacts with the other modules through the integrated database (see Strauch et al., 2005).

In ILUMASS, two distinct time scales can be recognized. Usually the simulation of traffic and the demand for transportation covers a short time period from seconds to weeks to reach its equilibrium, whereas the land-use development needs months to years. The output from the transport system is used as static input into the land use module, while the output from the land use module is used in the following year as an input into the transport module in a quasi-static way.

The ILUMASS land use model uses individual person and household micro data. Due to the fact that the retrieval of individual micro data from administrative registers for planning purposes is neither possible nor, for privacy reasons, desirable, the land-use model works with synthetic micro data (Moeckel, 2006; Moeckel et al., 2002). The synthetic population consists of households and persons that make activities, firms that provide workplaces and that offer goods or services, and buildings for residential, commercial, or public use and is updated annually. The statistical features of the agents in this synthetic population correspond to that of the real population. The synthetic population is updated annually in the land use module and used as input to the transport module.

The transport module uses the synthetic population as input for the activity generation model in the travel demand sub model. The activity generation model replicates and forecasts time dependent origin-destination matrices. For each simulated person the daily and weekly sequence of different activities and trips are generated. These aggregated trip tables by origin and destination and time of day are called activity programs.

In a first step for each person an individual activity repertoire is generated, which contains a set of activities and their characteristic attributes for execution e.g. duration, frequencies, priorities, and period of time (preferred start/end time) including an individual set of possible locations. In a second step, based on a skeleton schedule (routine or habitual activities), the different activities of the repertoire are put together in an individual activity programme (Strauch et al., 2005).

This travel demand is then converted to traffic loads on the network in the dynamic traffic assignment sub model.

3.4 How does it work: Theoretical foundation

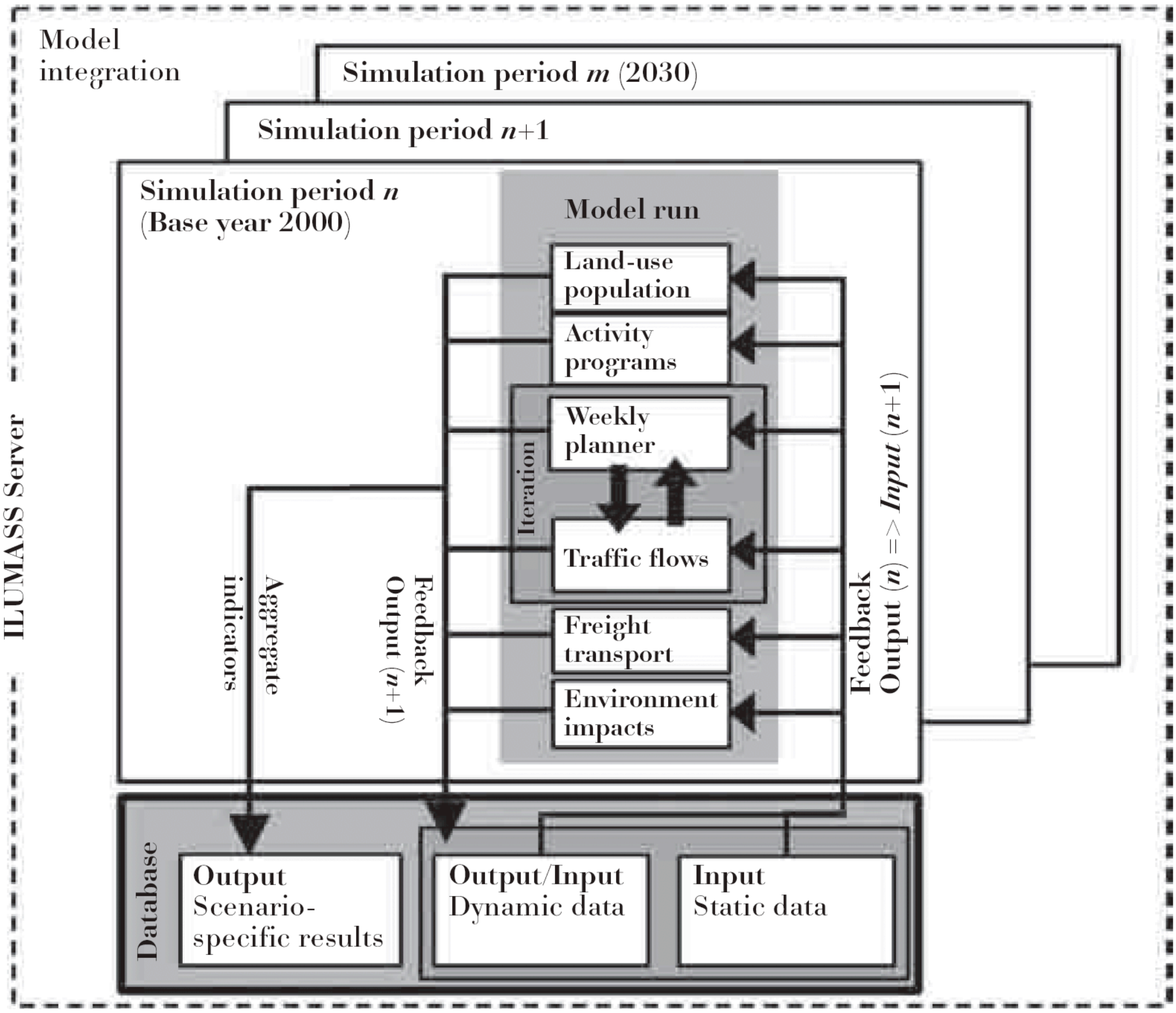
A model run of ILUMASS begins in the year 2000. It starts from the socio-demographic and spatial structure and generates from this the demand for transport, travel and freight transport and then the environmental impact of transport. These are then fed into the land use model for the following year, which generates a new socio-economic and spatial structure, which is used again as input to the transport module of the following year. In this manner, the state of the year 2000 is ``transported" into the future. By defining different scenarios that represent different policies, different trajectories of system evolution can be traced and subsequently analyzed for their effectiveness. This can help to identify successful and less successful policies at an early stage and to find better ideas on how the system can be optimized (Wagner & Wegener, 2007).

In the first year, the traffic simulation is similar to a classic four-stage travel demand model. After the first year, the feedback described above sets in and generates the fully dynamic evolution (see Figure 19). Within one simulation period, there is a direct interaction between the travel demand and traffic simulation: the traffic simulation returns travel times to the route choice sub model, which tries to drive the simulation to user equilibrium by assigning new routes to the simulation until it is in equilibrium, or, if this fails, asks the planner (the demand generation tool) to re-plan the activity programs of agents that do not have a feasible activity plan. This step guarantees the consistency of the model because, otherwise, the planning of the agents would be unconstrained and could include unrealistic plans. The travel times used in the planning of the agents should be in line with the true travel times in the network (Wagner & Wegener, 2007).

As the system proceeds from year to year, the feedback between transport and land use is affected. After each simulation period, the following data is available:

- Population, households, employment, firms, residences and industrial and commercial floor space and land use data by grid cell, traffic an analysis zone or municipality.
- A fully disaggregated demand for transport defined as trips from grid cell to grid cell by time of day or summarized in origin-destination matrices by mode of transport.
- Detailed information about network travel times from the traffic flow simulation, as well as traffic loads on each link of the network.
- An approximation of the demand for freight transport and business travel is computed by the freight transport sub model.
- Transport-generated air pollution, noise and other emissions for each grid cell, computed by the environment module.

Figure 19 Integration and data management in ILUMASS.



Source: (Mühlhans, Strauch 2004)

3.5 Case Study

The study area of ILUMASS is the urban region of Dortmund (see Figure 20). The area consists of the city of Dortmund and its 25 surrounding municipalities (macro level). The area is subdivided into 246 statistical zones. A much higher spatial resolution of 100 by 100 m raster cells (micro level) is applied for the transport and land use micro simulation as well as for modelling environmental impacts (Beckmann et al., 2007, Wagner, P. and M. Wegener, 2007).

The study region covers a population of about 2.6 million and 85 000 firms.

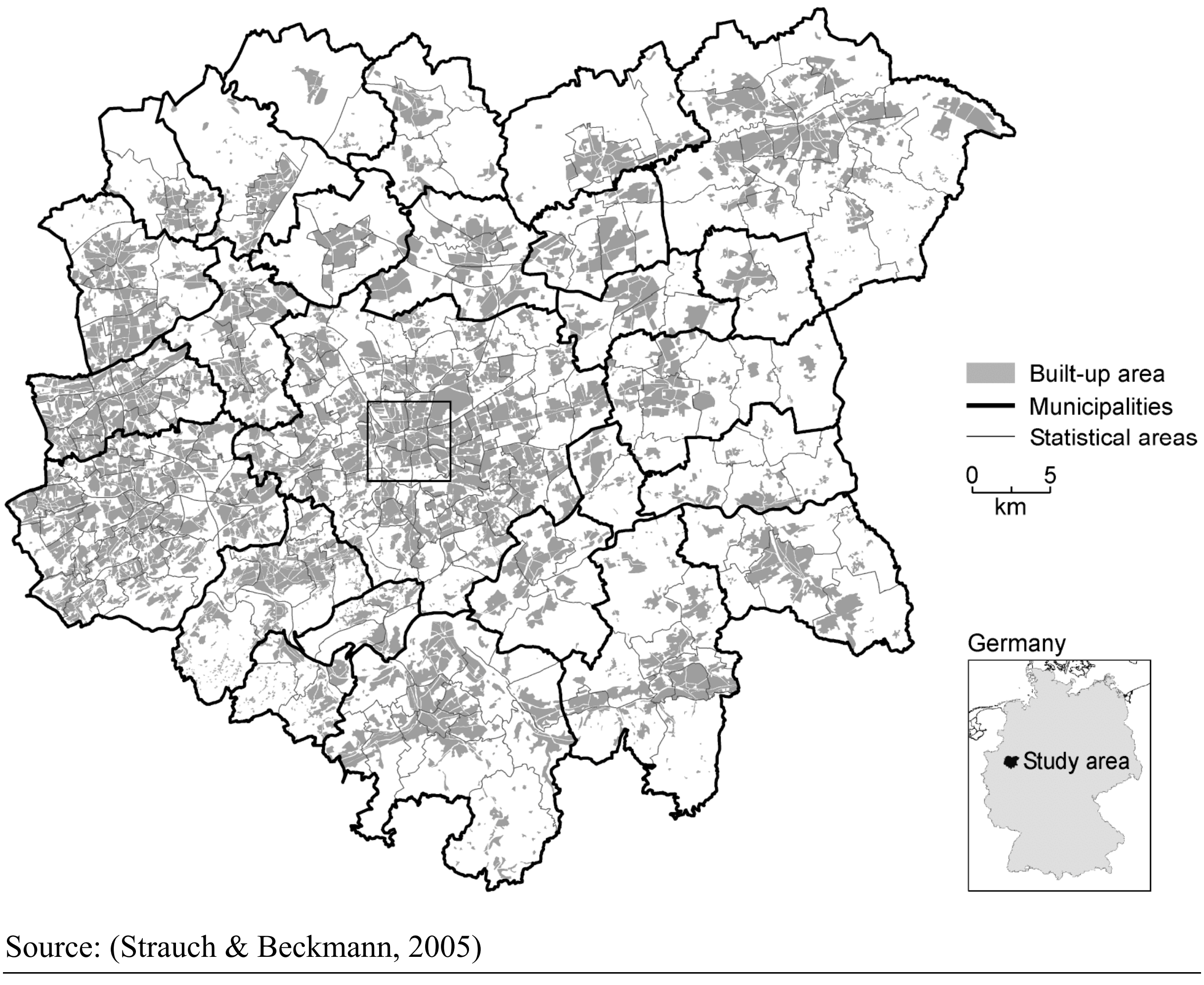
The base scenario of ILUMASS assumes the most likely future development of the spatial and transport infrastructure in the study area based on planning documents during development of this project.

The Dortmund region is affected by a profound change of various economic structures: In the past, this region was dominated by coal mining and steel manufacturing.

Although official sources in Dortmund assume a moderate population growth, the whole area is dominated by demographic and economic decline.

Because the project ran out of time, only a few test scenarios are executed. In these test scenarios only very basic checks for plausibility and consistency are made.

Figure 20 The study region of Dortmund and its 25 surrounding communities.



Source: (Strauch & Beckmann, 2005)

3.6 Hurdles in ILUMASS

Although the ILUMASS project greatly advanced the state-of-the-art in integrated urban models, the project ran out of funding before its complete implementation. Indeed every project is unique, but this section can help to surmount similar hurdles in other large projects. In the point of view of Wagner and Wegener (2007) the most important reasons for the partial failure of the ILUMASS project are:

- Application Programming Interfaces (API): The definitions of the interfaces (API) between the different modules had been structured very well. These interfaces are needed to connect the program modules developed at different research laboratories by “loose coupling”. However, the definition took more than one year. This time was missing in the end of the project.
- Testing: The testing process was inefficient. To test the functionality the simulation for the whole study area was run. End the end of a long run the simulation was useless because of slight errors in one other several modules. Defining small test cases where whole model chain can be run within second could speed up this process.
- Data exchange: Various source codes in this cooperative software development did not laid open, even not within the consortium. This led to a clumsy data exchange based on files. An open source project should be considered.
- Computing time: The computing time of a large microscopic simulation is time consuming. The most time consuming part, several hours to several weeks, was the calculation of travel demand, the calculation of shortest paths and the microscopic traffic flow simulation. The other parts do not take more than a few minutes of computer time. It might be necessary to work with multi-level models, which are microscopic where necessary and aggregate where an aggregate model is sufficient. It is hard to say where this trade off can be made.
- The cooperation between the project teams was difficult because of different disciplinary research traditions and scientific standards. It might have helped if the research groups could work together at the same location for several weeks.

3.7 Strengths and weaknesses of ILUMASS

This section is presented to summarize the weaknesses and strengths of the ILUMASS model. This comparison relies on the research of Ghauche (2010) that includes ILUMASS and ILUTE.

3.7.1 Strengths

Strengths in the **scope** of ILUMASS:

- Includes mobile energy and emissions
- Includes land use modifications
- Includes ecological processes
- Includes environmental indicators of sustainability
- Includes economic indicators of sustainability
- Includes social indicators of sustainability

Strengths in the **modelling approach** of ILUMASS:

- Bottom-up approach
- Includes households
- Includes individual activities
- High spatial resolution

Strengths in the **modelling techniques** of ILUMASS:

- Rule-based models Includes households
- Includes inter-individual interactions

3.7.2 Weaknesses

Weaknesses in the **scope** of ILUMASS:

- Does not include stationary
- Does not include impact of environment on transport
- Does not include environmental indicators of sustainability

Weaknesses in the **modelling approach** of ILUMASS:

- Does not include firms
- Does not include activity of firms

Weaknesses in the **modelling techniques** of ILUMASS:

- Does not include utility-based models
- Does not include intra-individual dynamics
- Does not include partnerships and competition between firms

4 UrbanSim

4.1 Starting with UrbanSim

UrbanSim is an urban simulation software developed by Paul Waddell, first with the support of his team at the University of Washington, Seattle, and now at the University of California, Berkeley. This model aims to simulate transformations in the two interacting systems that are transportation and land use, at the scale of a metropolitan area and over a long time span (typically 20-30 years). In its latest version, it is able to study the impact of environmental plans, land-use regulation (e.g. urban growth boundary, environmental restrictions, density constraints), and by coupling with a transport model, can examine transportation policies (new highways and arterials; new transit systems like bus, rail; various transportation pricing mechanisms like tolling, gasoline tax, congestion charging, etc.).

The motivation for the creation of the UrbanSim Software was to assist land use and transportation planning at the regional level within the context of growth management policies carried out at both the state and local level (Waddell, 2000). As a result, it puts special emphasis on transportation-land use interactions. To do so, UrbanSim models the behaviour of the key agents in the urban development process, namely households, firms, local authorities, and real estate developers, taking (among other things) the influence of transport conditions into account in their various decisions. Moreover, it follows a disaggregated approach. For instance, as far as households are concerned, UrbanSim simulates for each one in the study area yearly changes in composition (including creations/dissolutions), location, and employment.

Regarding the beginnings of UrbanSim, although it was first released on the web only in 1998 as Open Source software, development was initiated in 1996 through the Oregon Department of Transportation (ODOT)'s Transportation and Land Use Model Integration Project (TLUMIP). Stated more explicitly, through the fundamental project the ODOT funded in 1996 (i.e. TLUMIP) to establish new integrated land use-transportation models, two major outcomes stemmed, the first one was the implementation of a state-wide land use and transportation model and the second one was the development of UrbanSim (Waddell, 2002). It has been gradually improved since then with the financial support of the several grants funded by the National Science Foundation, the U.S. Environmental Protection Agency, and the Federal Highway Administration.

In order to acquire better knowledge of the UrbanSim software, several articles on the UrbanSim website provide useful information about the specification of the model, specifications of the case studies, analysis of its relationship to land supply monitoring, theoretical bases of the models, UrbanSim role as a decision support system (DSS), and data structure and data development procedure. Many of these items are covered by this report and the reader will find the citation to each item. Notwithstanding, we advise the reader to have a look at the UrbanSim community web portal at 'www.urbansim.org' where s/he can download the latest stable version of the UrbanSim software. Moreover, the Research section offers a list of papers, reports, and presentations from the whole UrbanSim community, with links to the documents in PDF format.

The UrbanSim software is released as Open Source software under the GNU General Public License (GNU GPL or simply GPL), which is broadly used under free software license. In particular, the GPL requires future upgrades to be accessible under the same copyright.

One of the key features of the UrbanSim software implementation is that it follows object-oriented programming (OOP). The OOP considers the data type (of a data structure) together with functions applied to the data structure. One of its advantages over procedural programming techniques is that it enables programmers to create new modules without any need to impose changes when a new object is added. It also enables the programmer to create a new object from existing objects. This makes object-oriented programs easier to modify.

Last but not least, UrbanSim is relatively flexible and enables the user to use his/her own models instead of the current general models that will be presented in the following sections.

4.2 Geographic Unit of Analysis

For the time being, three different geographic unit of analysis (GUA) can be employed in UrbanSim (UrbanSim-manual, 2009, chapter 17, pp.95-97) :

- Grid cells
- Parcels
- Zones

4.2.1 Grid cells

Most applications of UrbanSim have used the grid cell as the unit of analysis until now. The grid cell is the minimum resolution of geographic details that the user defined for the study. Accordingly, it can be said that, the smaller the size of the grid cell, the longer the computational time. The standard dimension of 150 meter by 150 meter was chosen in most studies so far, though the resolution can be selected by the user. However, more accurate approaches, parcels, were recently introduced in the latest versions of UrbanSim (see Figure 21).

Figure 21 Grid cells and parcels in UrbanSim

Source: (Waddell, 2002)

4.2.2 Parcels

The latest versions of UrbanSim allow the user to adopt a data structure based on parcels. Each building corresponds to one parcel, and households and jobs alike actually choose their building (and therefore parcel) when selecting their location. Land development (new development or redevelopment) also occurs at the parcel level.

4.2.3 Zones

UrbanSim allows the user to substitute any alternative data structure to the grid cells or parcels data structures. For example, traffic zones can be defined as the unit of analysis for an easier coordination with the transportation model.

Based on the experience gained from the SIMAURIF project (Laboratoire-THEMA, 2007) during which UrbanSim was calibrated for the Île-de-France (which corresponds more or less to the Paris metropolitan area), it was found that grid cells were not a relevant GUA given the structure of data for this area. Instead, it would be better to use a different GUA named *îlots.* A group of îlots comprise the larger geographical unit named *IRIS*, and combing IRISs together creates a *Commune*.

4.3 Model Structure

UrbanSim is not inherently an individual model; on the contrary, it is a tool for the integration of several models aimed at the simulation of urban development. Needless to say that each model deals with input data, output data, and a processing core transform the input data to the output. Within UrbanSim, six main models coordinate to receive the input data and produce the outputs. There are agents playing the main roles of the land development process in the real world. The UrbanSim models take the input data from agents and prepare the output for other agents.

4.3.1 UrbanSim object structure

Figure 21 shows the object structure of the UrbanSim model with their related features. This diagram demonstrates the real-world interconnections among the agents who play the major roles in urban structure developments. The objects are:

- **Developers** who construct new **buildings** (new development) or redevelop the current ones. They are responsible for making decisions about the type of development for each GUA including no development in each GUA, the density increase for each one within the current development type, or the evolution of the GUAs to another development type. The supply side of the urban development is directly change by the decision of these agents.
- **Buildings** are located on land parcels that have particular characteristics such as value, land use, slope, and other environmental characteristics.

- The land development is performed in such a way as to not violate the **policies** set by **governments** to impose restrictions on conversion of land, density constraints, development impact fees, infrastructure costs, urban growth boundary, and environmental restrictions (e.g. see Table 5 in Waddell, Liu, & Wang, 2008). In addition, governments construct **infrastructures** giving services to the agents occupying the land. The most important service is providing accessibility by transportation infrastructures.
- **Households** and **businesses** are the agents occupying the building.

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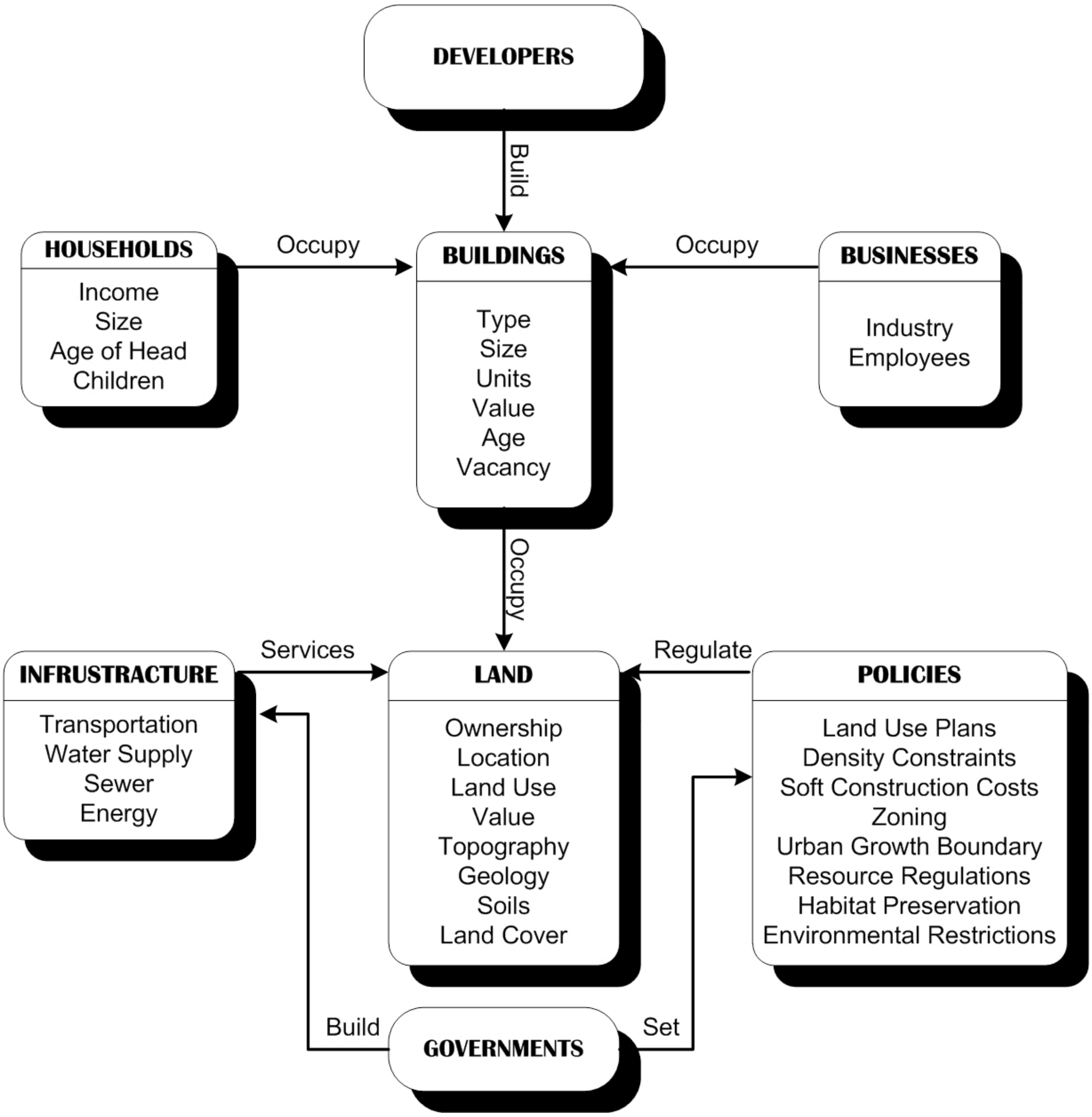
Figure 22 UrbanSim model object structure

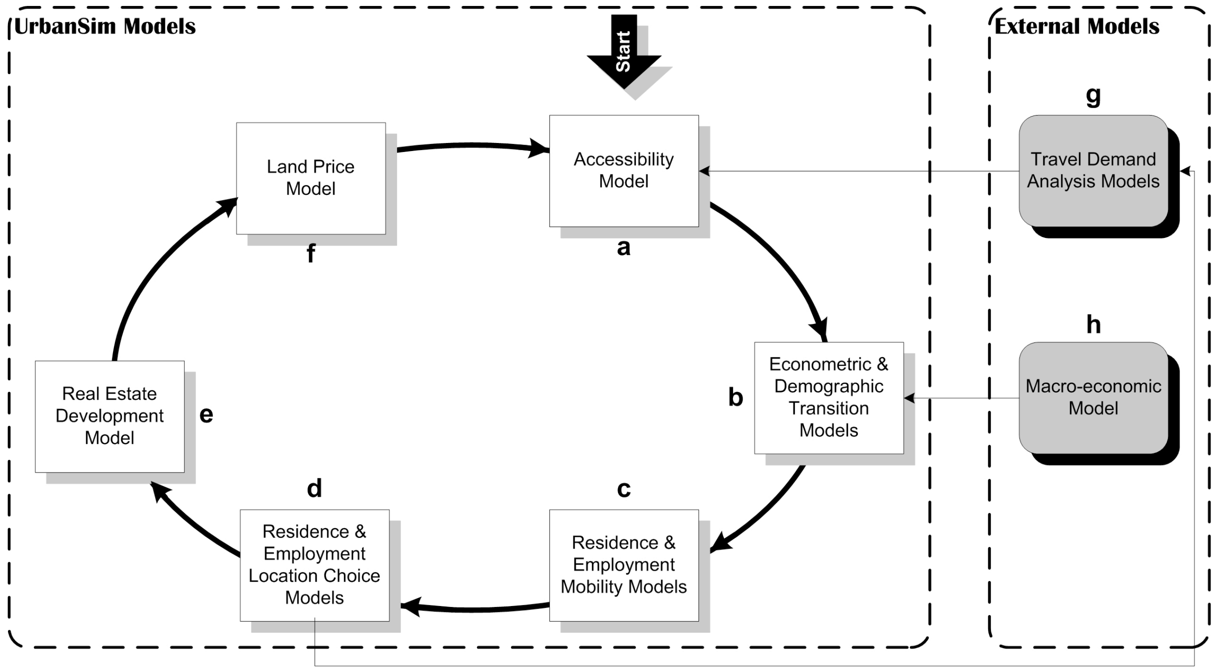


Source: (Waddell et al., 2008; Waddell & Ulfarsson, 2004)

4.3.2 Main models and their interconnections

Figure 23 provides the main models and their sequence without dealing meticulously with complex software architecture and the object structure. As can be seen, UrbanSim is mainly composed of six main models which are the accessibility model, the demographic and economic transition models, the household and employment mobility models, the household and employment location models (relocation models, real estate development model (developer model), and the real estate price model. The bold arrows in Figure 23 do not necessarily imply that there is an interaction between the corresponding models, and only show the sequence of events. Only the arrows between the external models (travel demand analysis model and macro-economic model) and the internal ones represent data flows.

Figure 23 The sequence of UrbanSim main models.



Let us now describe the various models:

a. **Accessibility model:** prepare the pattern of accessibility by the use of data derived from transportation demand analysis models. Accessibility is fed into residential and employment location choice models, as well as real estate development model.

b. **Demographic and economic transition models:** simulates births and deaths in the population of households by type and models creations and losses in the job by type. The new households and jobs will find locations later by household and employment location choice models.

c. **Household and employment mobility models (relocation models):** models the movement of households or jobs inside the region. The relocating households or jobs are placed in the queue to find new location for them by the location choice models. Their last locations also are made available. As well as interaction with location choice models, these models change the real estate and vacancies conditions, which are used later in the real estate price and developer models.

d. **Household and employment location choice models:** selects a location for each household and job that has no current location from the available vacant real estate. A workplace choice model, which *connects* persons to jobs, can be run as well if UrbanSim is configured to do so.

e. **Real estate development model (developer model):** models the developer decision making about the place, type, and number of new development and redevelopment of existing structures.

f. **Real estate price model:** simulates real estate prices of each GUA. It provides input data for real estate development model and for household and employment location choice models.

Moreover, the external models, which will be described further in section 5, are as follows:

g. **Travel demand analysis model:** estimate the zone-to-zone congested travel times and composite utilities of travel.

h. **Macroeconomic model:** predict future macroeconomic conditions such as population and employment by sector.

4.3.3 How do the models work: Theoretical foundation

The theoretical framework of the UrbanSim models have been presented in several articles and references as (de Palma, Picard, & Waddell, 2007; UrbanSim-manual, 2009; Waddell, Bhat, Eluru, Wang, & Pendyala, 2007; Waddell et al., 2003; Waddell & Ulfarsson, 2003; Waddell, Ulfarsson, Franklin, & Lobb, 2007; Waddell & Ulfarsson, 2004). Here, we just concisely describe the theory behind the model and explain some of its econometrical properties.

Accessibility

The accessibility calculations in UrbanSim transform the transportation data provided by an external traffic model (e.g. see "MATSim- Multi Agent Transport Simulation Toolkit," 2010; METROPOLIS 1.4 manual," 2010) into accessibility measures. We are going to explain it in detail later in section 4.5, which is 'Interaction with travel demand models.

Demographic and economic transition models

Economic transition model

Firstly, it should be noted that the prediction of the change in the number of jobs is not performed inside UrbanSim; on the contrary, macroeconomic models exterior to the UrbanSim environment come in to predict the total number of jobs, and potentially other aggregate information about it. That is, the predicted future employment is derived by a macroeconomic model that is exogenous to UrbanSim. The task of the economic transition model is to integrate the aggregate exterior forecast from macroeconomic models with the database inside UrbanSim for each sector of employments, which consists of typically 10 to 20 employment sectors. It provides for each year the increase or decrease in the number of jobs by sectors by considering constraints (control totals) as the external assumptions about economic growth or decline within sectors over the period of one year.

To do this, jobs are randomly sampled from the simulation database to be added or deleted as needed to meet the control totals. For employment, control totals are usually by employment sector, but may also be split by whether the jobs are home-based or not.

The new jobs are given a location by the subsequent employment location choice model, as explained in the following sections. The jobs that are removed leave a vacant location, which is available for other new or relocating jobs.

Demographic transition model

The demographic transition model serves a similar role as the economic transition model. It interfaces with external data calculated by external macroeconomic models about the total population, and potentially other aggregate data such as household size and income distributions. The demographic transition model determines the total number of household (by type) in the UrbanSim database by the comparison between the anticipated total amount of households for the future years and UrbanSim database. It determines the number of household to be added or deleted in each demographic sector in order to meet the external control totals, and randomly samples households in the simulation database to add or delete to meet these targets

Household and employment mobility models

Mobility models are also named as the *Relocation Models*. They are classed into household mobility model and employment mobility model.

Employment mobility model

There are several reasons for employ displacements as job turnovers by employees, layoffs, business relocations, or closures (UrbanSim-manual, 2009; Waddell et al., 2003). In this regard, the employment mobility model of the UrbanSim software simulates employment motilities because of these above-mentioned reasons. It uses external historical data which is the input data used as the probability (relative frequency) of employment movement from their current positions, and predicts that jobs (of each type) relocating from their current location or staying during a particular year.

Employment mobility model employs a very simple algorithm to derive the number of relocated jobs equal to the exogenous annual job mobility rates (by sector). Suppose R_{kt} is the number of jobs in sector *k*, which should be selected for the re-location in year *t* (k: 1, …, K; t:1, …, T). If N_{kt} were the number of total jobs in sector *k* in year *t*, the ratio R_{kt}/N_{kt} should meet the job mobility rate in sector *k* for year *t*. To do so, we leverage a Monte Carlo sampling process generating N_{kt} [0,1]-uniform random numbers for N_{kt} jobs. For each job if the number is smaller than the job mobility rate in sector *k* for year *t,* then it is selected to move, and consequently, it is placed in the limbo to indicate that it does not own currently a position. Its past position, as a result, is made available. That is, the results of employment mobility model are moved jobs having no place, and locations having no jobs. Both of these data will be relaxed by the employment location choice model, which will be described later.

Note that UrbanSim now has a flexible infrastructure to add choice models, and it would be relatively straightforward to add binary logit models for the relocation choice. If panel data is available for firms, it may also be possible to construct a nested model of relocation and location choice, which would be theoretically preferable to independent models. This will need to be further explored.

Household mobility model

Basically household mobility model perform in an analogous fashion to employment mobility model described above. That is, external mobility rates (by sector) are used as the benchmark by which the model simulates the household relocations year-by-year. The mobility probability (i.e. mobility rate) is usually estimated from census of population surveys. These rates are obviously different for renters, owners, and different household sectors.

When the mover households are distinguished, they will be added to the pool of household having no place currently exactly like the new households come into existence by the last demographic transition model. That is the combination of new and moving households creates a group should be fed into the following household (residential) location choice model.

Household and employment location choice models

Employment location choice model

The Employment location choice model simulates the location choice for:

1. Old jobs deemed to move based on the indigenous forecast of employment mobility models inside UrbanSim (i.e. employment relocation model component of UrbanSim)
2. New jobs generated as a result of economic expansions, which are derived through exogenous forecast of external macroeconomic model (see Figure 1).

In other words, in this model we have vacant job location units as our decision alternatives, and the employments as our decision makers. As the first step, the software determines whether or not there is a free place in each GUA. For the jobs, not having any location, the employment location choice model comes finds them new locations. For the location choice model it is supposed that (a) each job, belonging to a firm, encounter a choice situation among several location as the decision alternatives, (b) for each location, a utility (comprised of systematic utility and random one) is considered by the job belonging to the specific firm, and finally (c) that the job choice the location with the highest utility amongst alternative set (utility maximization). Note that in some applications of UrbanSim, such as in San Francisco, the business establishment has been used as the decision-maker.

Using the Random Utility Maximization (RUM), we assume that each alternative i in the job location market is received a final utility U_i, which consist of a systematic (or fixed) utility and an unobserved (or random) utility:

$$U_i = V_i + \varepsilon_i, \quad i = 1, \cdots, n \tag{1}$$

Where $V_i = \alpha \times x_i$ is a linear function, α stands for the vector of coefficients drawn from method of maximum likelihood estimation (MLE), x_i points to the vector of alternative characteristics, n refers to the number of alternatives, and ε_i is an unobserved random utility parameter distributed with extreme value type I distribution ending to multinomial logit model pioneered by McFadden (McFadden, 1974):

$$P_i = \frac{e^{V_i}}{\sum_j^n e^{V_j}} \quad (2)$$

Where *j* is the alternative index (j=1,.., n) indexes.

Based on (Waddell, Ulfarsson et al., 2007), variables used in the factors can be employed to estimate the systematic utility of each location in the location demand model can be divided into three following tree main categories:

- Multi-modal *accessibility* (x_A) to:
  - Labour
  - Consumers
  - The Central Business District (CBD)
  - The regional airport
- *Site* characteristics (x_S):
  - Real estate characteristics (land value, residential units, commercial square foot, and land use)
  - Proximity of the site to freeways and arterials
  - Characteristics of the land use mix and value
- *Neighbourhood* surrounding the site (x_N)
- *Geographic clustering* (x_G) of firms of the same (employment by sector within 600 m)

As can be seen above, the accessibility criterion derived from transportation models directly affect the process of job location choices.

In the light of aforementioned explanations, in the employment location choice model, we have the systematic utility of each location as follows (adding index *e* referring to employment choices and removing index *i* for simplicity):

$$V^e = \alpha_A^e x_A^e + \alpha_S^e x_S^e + \alpha_N^e x_N^e + \alpha_G^e x_G^e \quad (3)$$

In brief, the employment location choice model simulates the mechanism of choosing location alternative *i* for a particular employment by a specific firm. Furthermore, for different industry sectors (e.g. Health Service sector, Restaurant and Food Store service, etc) we estimate different choice models (i.e. different set of $\{\alpha_A^e, \alpha_S^e, \alpha_N^e, \alpha_G^e\}$.

Residential location choice model

Because the theoretical framework behind the residential location choice model is similar to the employment location choice model, being based on a multinomial logit model, it is only briefly described here.

The decision alternatives inside this model are GUAs. Each GUA can include null or several housing units. It is important to note that because all the housing units on a grid cell (or zone) are assumed identical, the households are not assigned to a specific housing unit. The systematic utility model for each location is derived by (adding index *r* referring to residential choices and removing index *i* for simplicity):

$$V^r = c^r + \alpha_H^r x_H^r + \alpha_A^r x_A^r + \alpha_N^r x_N^r \qquad (4)$$

Where each above utility terms can be composed of a linear combination of different variables categorized into (Waddell et al., 2008):

- H represents housing characteristics as
  - Net density of a particular housing type in a zone (units/acre)
  - Number of housing units of a particular type in the zone
  - Average age of the buildings of a type in a zone
  - Price

- R indicates regional accessibility measures such as
  - Multi-modal access to employment opportunities
  - Travel time to the classic monocentric CBD (in minutes)
  - Travel time to airport
  - Distance to highway
- N reflects neighbourhood-scale effects such as
  - Percent of households in a zone in:

    -The lowest income group
    -The second lowest income group
    -The highest income group
  - Percent of the households in a zone that have one or more children

- Percent of the developed land in the zone that is in industrial use
- Percent of the developed land in a zone that is in residential use
- Density
- Local accessibility (local shopping)

Needless to say that not only may the calibration require further variables, but also we put into use statistical tests and further calibration to determine which above-mentioned variables are more suitable for our model. For example in Waddell, et al (2007, p. 394, Table 3) the specific initial variables used in the residential location choice model were revised based on initial testing of the integrated model. That is, they changed their variables after they compared the base year simulation results, which had been derived from UrbanSim, with the real base year data.

Note here that if a workplace choice model is added, as was done in the Seattle application of UrbanSim, it is also possible to add variables representing the individual worker accessibility to their specific workplace. This was found to significantly improve the predictions of the household location choice model in Seattle. Other improvements there included the use of previous residential location, which allowed adding variables for the new location being close to the old one, or of a similar type of neighbourhood – both of which were significant effects.

Real estate development model

We need to identify the future development projects at each position within the study area in each year to have an updated supply database on available real estates and vacancies which play significant role in the residential and employment location choice models, and furthermore, in the land price model. There are two type of developments as the *greenfield development* which refers to a new development and *infill and redevelopment* points to a conversion of current development (Waddell, Ulfarsson et al., 2007).

Land Transition Model

There are three different approaches that have been used by UrbanSim to model real estate development outcomes. The first one is what we will call the land transition model. It takes the perspective of the landowner of a piece of land (grid cell or parcel), and predicts the transition in a given year from the current state of development, to a different state of development. This subsection describes this approach, though it has in fact only been used in the grid cell model applications, and not in more recent parcel or zone level model applications.

The real estate development model interrelates with the two preceding models. That is, the placed households and jobs derived from residential location choice model and employment location choice model are used as the input data for modelling the developer's decision making behaviour in considering a possible transition for the decision alternatives which are the GUAs here. Another input data enters into this procedure is land prices calculated for each simulated year by the land price model that will be described in the subsequent section.

The real estate development model in UrbanSim uses a multinomial logit model to determine which of the following events occurs for each GUA:

- No development (do nothing)
- Increase in the density of GUA but based on the current development type
- Evolution to another development type

Stated more clearly, for each GUA we have a probability that a developer considers one of the aforesaid development alternatives. For each development alternative *i,* a utility composed of a deterministic term and an extreme value random term ($U_i = V_i + \varepsilon_i$) is calculated. Then, the one with the highest utility (U_i) is selected.

For the calibration of our model, we should consider those GUAs experiencing any type of developments. For these GUAs, the data are entered from the GUAs database to estimate the coefficient of the model as follows (Waddell, 2002; Waddell & Ulfarsson, 2003; Waddell, Ulfarsson et al., 2007):

- Characteristics of the GUA (x_G)
  - Current development
  - Land use plan
  - Environmental constraints
  - Policy constraints
  - Land and improvement value
- Characteristics of the site location (x_S) with respect to proximity to
  - Highways
  - Arterials
  - Existing development
  - Recent development
- Characteristics of the neighbourhood surrounding the site (x_N);
  - Characteristics of the land use mix
  - Property values

  - Local accessibility measures
- Multimodal accessibility (x_A)
  - Access to population and employment
  - Travel time to the central business strict
  - Travel time to the airport

Hence, the fixed utility models is derived as (adding index *d* referring to developer choices and removing index` *i* for simplicity):

$$V^r = c^r + \alpha_G^r x_G^r + \alpha_S^r x_S^r + \alpha_N^r x_N^r + \alpha_A^r x_A^r \qquad (5)$$

One limitation of the land transition model is that it does not reflect the role of the developer who is shopping among locations for the most profitable site for specific projects. The next approach takes this perspective.

Development Project Location Choice Model

The second approach to modelling real estate development events implemented in UrbanSim is one that takes the perspective of a specialized developer (for example, one that builds office buildings), and frames the model as a location choice model for that type of project. There are as many sub models as needed to represent different types of properties (building types), and developers are assumed to choose locations in order to maximize their profit.

This framework for the model parallels the household and business location choice models, and adds some flexibility to the model system, by allowing the GUA to be modified relatively easily. It also has somewhat better realism in representing the effects of alternative policies that might restrict development in certain areas, or change the allowable densities for development.

The creation of projects to be located occurs in a development_project_transition_model, which compares the current vacancy rates to long term vacancy rates that are considered threshold levels, below which we expect developers to become active, and above which we expect that profit levels would be low and risk levels high, therefore inhibiting new development. When vacancy rates for a building type fall below the structural vacancy rates set in user input tables, then the model samples enough existing buildings to satisfy the target vacancy rate, and generates new buildings with these attributes. They are then located using a standard MNL model using parcels (or zones) as the location alternatives, and taking into consideration the capacity constraints imposed by land use regulations.

One limitation of this approach, as one might anticipate, is that this reflects only the developer perspective and not the landowner. The two are complementary, and probably both are at work in the market at any time. In addition, using this approach, we can add buildings to a parcel or zone, but it is difficult to directly model redevelopment.

Development Project Proposal Choice Model

This approach to modelling real estate development attempts to bring the landowner and developer perspectives together. The methodology is fully described in Wang and Waddell (2010). In brief, this approach considers each parcel, and evaluates a set of development templates that provide an inventory of alternative types of development and densities. Within the size of the parcel and the development regulations that apply to it, one or more templates might be feasible to build on the parcel. These templates become proposals that can be considered for that parcel.

Once a set of proposals has been generated for each parcel, a return on investment calculation is done for each proposal. The expected revenue from constructing a proposal is computed using the hedonic price models estimated for different building types, substituting the attributes of the proposed building for whatever building characteristics are currently on the site (if it is a redevelopment) or adding it to the site if it is an infill project that is being added to a parcel. Costs of development are considered as well, including the acquisition of the site (the initial value of the parcel), the demolition costs if required, the construction costs for the new development, and any additional costs, such as infrastructure extension, or policies that tax or subsidize development.

Real estate price model

The real estate price model predicts the price of real estate. It is clear that the land value plays an important role in different manner of urban development as was seen through its key function in residential and location choice models, and moreover, the real estate development model where land prices directly enters the utility functions. The real estate price model estimate property values at different locations and with various types of land use through a mechanism embodying the two following approaches:

- Relative prices level: There are several features affect the land spatial values from one place to another one within the study area. These factors, which establish relative land values, are grouped in the three following categories (UrbanSim-manual, 2009; Waddell et al., 2003):

- Site characteristics
  - Development type
  - Land use plan
  - Environmental constraint
- Regional accessibility
  - Access to population
  - Access to employment
- Urban design-scale
  - Land use mix and density
  - Proximity to highway and arterials

• Overall price level: As well as the relative price level captured by the aforesaid items, the overall price level should be also considered for calculating temporal land price (for each type of real estate). In other words, the overall land price might change over time because of the fluctuations in supply and demand. This item is taken through the difference between the current year market vacancy rate and the long-term vacancy rate. For example providing that the current year vacancy rate descends below the long-term vacancy rate, land price levels rise.

Both of the above price levels are merged in the real estate price model forming the following hedonic regression model (Kakaraparthi & Kockelman, 2009; Waddell et al., 2003):

$$P_{ilt} = \alpha + \delta\left(\frac{V_i^S - V_{it}^c}{V_i^S}\right) + \beta X_{ilt} \quad (6)$$

Where index i refers to the building type, index l points to the location, and t captures the time.

Where P_{ilt} is the land price per unit of development, V_{it}^c is the current vacancy rate, V_i^s is the long-term structural vacancy rate, X_{ilt} is a vector of locational and site attributes, and α, δ and β are estimated parameters. Note that in many applications of UrbanSim, there has not been sufficient vacancy rate information to estimate this vacancy adjustment term, and it is not included in those applications.

After the real estate prices are calculated at the end of year and the database is consequently updated, the new real estate prices are going to be used by residential and location choice models and real estate development model for the following year.

Table 2 provides the summary of input and output data for each UrbanSim models and the external models.

Table 2 Input and output for the models

	Model	**Input**	**Output**
UrbanSim models	a. Travel Model Interface	Transportation measures from travel demand models + Placed jobs and households	Accessibility measures
	b. Economic and demographic transition model	Total number of jobs and households per year	Unplaced jobs and households in each GUA
	c. Household and employment mobility model	Historical data on the rata of mobility + Placed jobs and households in each GUA	Unplaced jobs and households in each GUA + Real estate vacancies
	d. Household and employment location choice model	Accessibility measures + Unplaced jobs and households in each GUA + Placed jobs and households in each GUA + Real estate price + Real estate vacancies	Placed jobs and households in each GUA + Real estate vacancies
	e. Real estate development model	Placed jobs and households in each GUA + External rules for land development + Accessibility measures + Real estate price	New real estate vacancies
	f. Real estate price model	Accessibility measures + Placed jobs and households in each GUA + Real estate vacancies	Real estate price
External models	g. Travel demand analysis model	Placed jobs and households in each GUA	Transportation measures
	h. Macroeconomic model	Not from UrbanSim	Total number of jobs and households per year

4.4 Architecture

We describe the UrbanSim software architecture from two points of view that are functional architecture and physical architecture.

4.4.1 UrbanSim functional architecture

The functional UrbanSim architecture is an architectural model that shows main operational elements, their functions, interactions and corresponding data needs. The structure and processing sequence of UrbanSim are presented in Figure 24 (Waddell et al., 2008). The elements in the UrbanSim model functional architecture is classified into the three following components as:

- Data: flows within and between models as well as between external entities like external models and user inputs. The data rest in a database shown in the centre of Figure 24.
- Models: as mentioned in section 4.3.2, there are six main models inside UrbanSim which are travel model interface, demographic and economic transition models, household and employment mobility models, household and employment location choice models, real estate development model, and real estate price model.
- External components: contain external models (travel demand analysis model and macroeconomic model) and user inputs including user specific events and scenario assumptions.

In Figure 24, inputs fed into the model are:

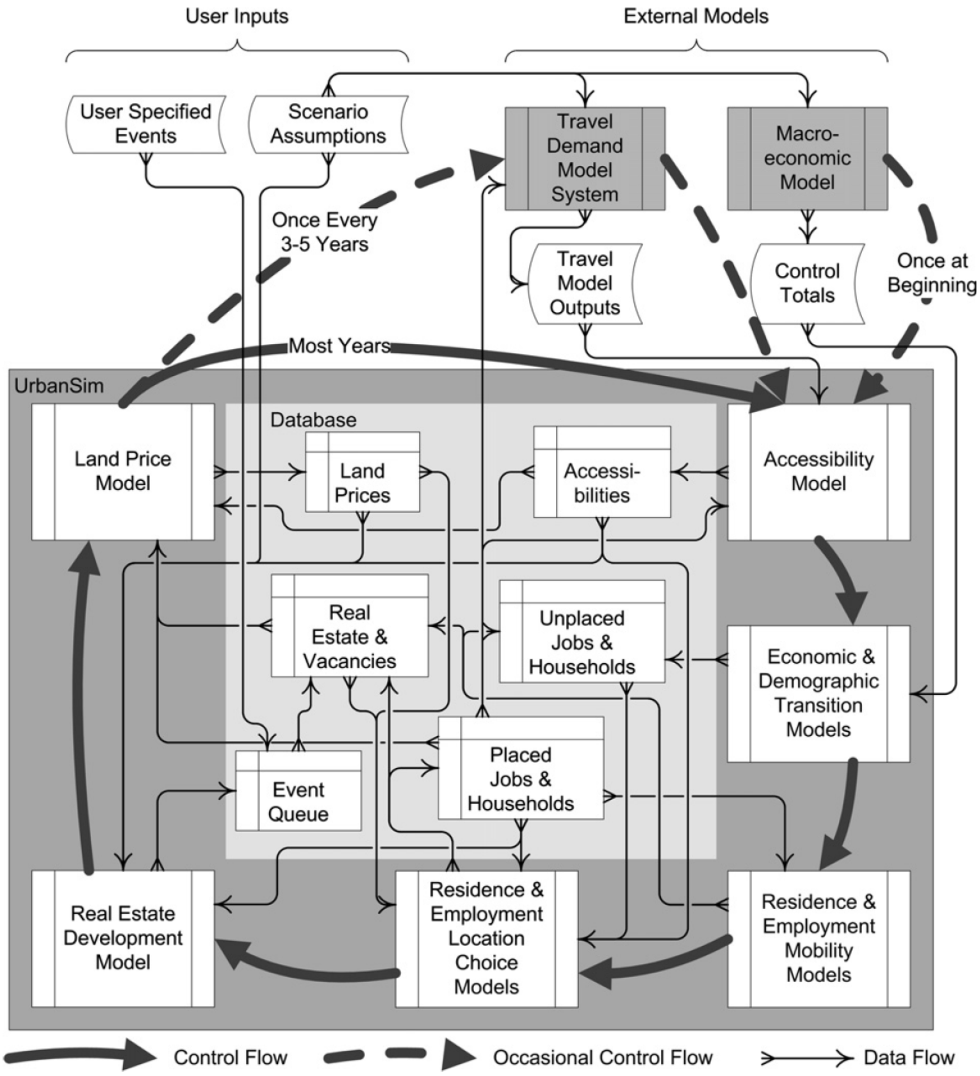
- The base year data store as:
  - Employment data
  - Household data
  - Parcel database (with acreage, land use, housing units, non-residential square footage, year built, land value, improvement value, city and county)
  - Land use plan
  - GIS overlays for environmental features (wetlands, floodway's, steep slopes, etc.)
  - Traffic analysis zones
  - GIS overlays for planning boundaries
  - Travel model outputs
  - Development costs
- Control totals derived from external regional economic forecasts

- Travel data derived from travel demand analysis models
- User inputs consisting scenario policy assumptions as:
  - Land use plans
  - Density constraints
  - Soft construction costs (fees, costs, taxes or subsidies)
  - Urban growth boundary,
  - Environmental restrictions,
  - Special planning for exceptional policies

Considered together as a system, the models and components preserve the input data; simulate its evolution gradually year-by-year and save the new produces data in the data store.

Externally developed control totals for households provide target values for the transition models, which can operate on more detail sub-categories of households (by distribution of income groups, age, size, and presence or absence of children) and employment (by distribution of business sector).

Figure 24 UrbanSim functional architecture



Source: (Waddell, Ulfarsson et al., 2007)

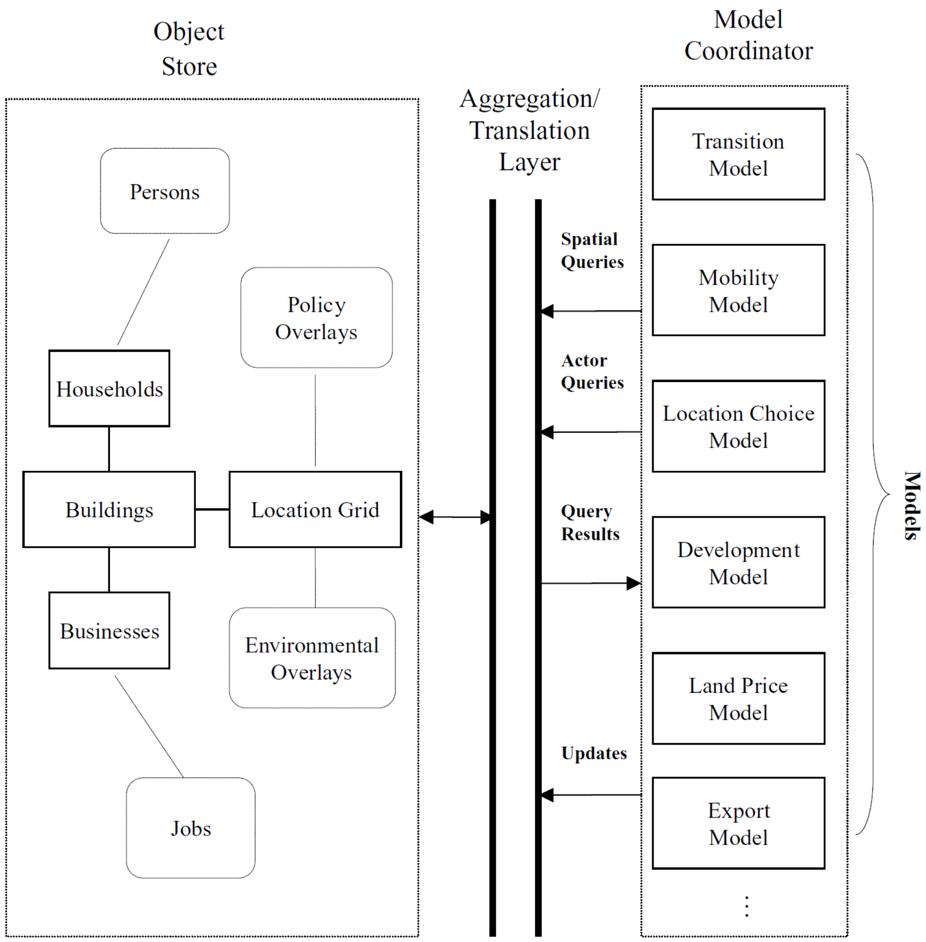
4.4.2 UrbanSim physical architecture

The UrbanSim software physical architecture is the structure, which comprises principal software components and their relationships. That is, beyond the models and data flows, we have some components that integrate and coordinate several models and translate the data from one component to be readable for another one.

The UrbanSim physical architecture in UrbanSim version 3 has been described completely in (Noth, Borning, & Waddell, 2003). Stated concisely, as shown in Figure 25 the UrbanSim physical architecture contains mainly four principal components:

- **Models** that encode the behaviour of agents in the simulation,
- A **model coordinator** that manages, and moreover, schedules the order of running the models and informs the models when their related input data has updated,
- An **object store** that keeps during the simulation the shared representations of objects mentioned in section 4.3.1 and also other entities like policy overlays and environmental overlays, and
- An **aggregation and translation layer** that performs a range of data conversions to intervene between the objects and the models.

Figure 25 UrbanSim physical architecture



Source: (Noth et al., 2003)

In Figure 25, the Export Model is the output module, which is implemented as a model because of software engineering reasons.

Much of this general architecture description remains relevant to UrbanSim version 4, which was reimplemented from Java to Python in version 4. A complete description of the design of the architecture of the current version of the software is available in the UrbanSim documentation.

4.5 Interaction with travel demand models

The interaction between UrbanSim and Travel demand models is a bi-directional interrelationship. The UrbanSim software provides the number of households and the number of jobs in each traffic zone, resulting in the OD matrix. The travel demand models also provide the necessary data ending to the accessibility measures used in different UrbanSim models (see Table 2).

The accessibility is computed for each GUA based on its role as an origin and as a destination. We have(de Palma, Motamedi, Moyano, Nguyen-Luong, & Picard, 2005):

$$A_{ai}^{O} = \sum_{j}^{J} E_j e^{L_{aij}}, \; A_{ai}^{D} = \sum_{j}^{J} P_j e^{L_{aij}}, \quad (6)$$

where index a is the auto-ownership category, A_{ai}^{O} is the accessibility of GUA i as origin and A_{ai}^{D} is the accessibility of GUA i as destination, P_j is the number of population that travel to the GUA i for working there, Ej is the job places to which the people travel, and L_{ij} is composite utility, or logsum, for vehicle ownership category a, from location i to j.

Numerous other measures of accessibility are also available in UrbanSim. If skims for OD pairs are extracted from the travel model by purpose, mode, and time of day, using time and/or generalized cost, then it is possible to compute isochrone type measures of the amount of certain types of activities accessible within specified time frames, by mode. There is no restriction on the nature of these accessibility measures that can be used, and a substantial number have already been coded in UrbanSim and used in a variety of applications. As noted earlier, it is also possible to compute individual-specific accessibility measures, such as log sum, time, or generalized cost for the commute trip for a worker, if the workplace choice is modelled in UrbanSim.

4.6 Case studies

In the paper by Waddell and his colleagues (2008, pp. 9-12), a section has been dedicated to reviews some of the applications of UrbanSim in real world referring to the numerous application of UrbanSim such as in Honolulu, Hawaii; Eugene-Springfield, Oregon; Houston, Texas; Salt Lake City, Utah; Seattle, Washington; and San Francisco, California.

In Europe and in Paris, through the project SIMAURIF (SIMulation of the interAction between land Use and transport in the Region Paris Ile-de-France) defined by the regional planning agency for the Paris metropolitan region, IAURIF, in coordination with the University of Cergy-Pontoise, UrbanSim was used for the Paris region. It was one of the largest applications of the model system, to date, with 11 million inhabitants in the region (Laboratoire-THEMA, 2007).

Furthermore, UrbanSim was employed in the research project "Infrastructure, accessibility and spatial development" for the Greater Zurich area intending to simulate the integrated land use and transport development (Löchl, 2006). It also employed in study for the city of Brussels (Patterson & Bierlaire, 2007). Regarding other examples of UrbanSim Application Throughout the Europe we can refer to Lyon, Lausanne, Rome, Tel-Aviv, Amsterdam, and Turin (Vanegas, Aliaga, Beneš, & Waddell, 2009).

4.7 Key Features of UrbanSim

The key features of UrbanSim are:

- The model disaggregately simulates the behaviour of the key decision makers (households, businesses, and developers) who have the major impact on urban development.
- The model simulates urban development dynamically as a spatial and temporal dynamic process.
- This software deals with the land market change over time as the supply side of the urban developments.
- It, furthermore, considers the iteration between demand side (housefuls and firms location demand) and supply side (real estate vacancies).
- UrbanSim consider governmental impositions on conversion of land, density constraints, development impact fees, infrastructure costs, urban growth boundary, and environment.
- The agent (households, businesses, and developers) choice models are based on the random utility models. It incorporates multinational logit models to simulate the decision-making behaviour.
- It also uses the hedonic regression model for the land price analysis.
- UrbanSim is Open Source software using the GPL license.

- It is compatible with windows, Linux, and Apple OS X.
- It is freely downloadable though internet from www.urbansim.org
- It follows object-oriented programming (OOP enabling programmers to create new modules without any need to impose changes when a new object is added.
- It is able to have a very good interaction in input and output data with ArcGIS or other GIS software.

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