Agent-based land use transport interaction modeling: state of the art

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1 Introduction

Land use transport interaction (LUTI) models try to capture the feedback between land use schemes and transport to improve urban planning. Transport and land use are influencing each other in a dynamic and complex manner (Alonso 1964, Mills 1967, Muth 1969, Anas 1982, Borzacchiello et al. 2010). Accessibility, provided by transport, influences location decisions of developers, firms and households (Hansen 1959, Moeckel 2006). Conversely, land use determines the need for spatial interaction (Wegener 2004, Strauch et al. 2005, Wegener 2011). Hence, modeling processes of the urban system needs an integrated view of the interactions between land use and transport (Wagner & Wegener 2007). LUTI models are taking those interactions into account. They are increasingly used in impact analysis and the evaluation of transport, land use and environmental policies (Lee 2009). They help planners and decision-makers assessing the impact of infrastructure measures and to improve policy and investment decisions.

The aim of this chapter is to discuss strengths and weaknesses of such integrated models. To do this, first (i) general aspects of integrated models are discussed and (ii) important evolution steps of land use and transport models are summarized. In order to characterize LUTI models (iii) important underlying subsystems are identified and discussed. Next, (iv) based on the review by Wegener (2004) an overview of existing LUTI models is provided. Finally, (v) a selection of disaggregated and

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agent-based models are discussed in greater detail. These are ILUTE, ILUMASS and UrbanSim. The chapter finishes with the conclusions.

2 A framework of urban systems

We can define LUTI models as simplifications of the urban system to do impact analysis and evaluation of policies and planning with respect to a defined targets. The main purpose is to understand how land use and transport influence each other and consequently to use the knowledge to explain effects of modifications to the urban system. If we know the sensitivity of households towards a cordon toll, we have a better idea about the consequences on the city center's housing market. The effects can then be evaluated with respect to defined targets to improve planning. To establish a common understanding we describe the object for which the model is built, discuss general aspects in modeling and define the most important terms. This allows us to put LUTI models within this context. The review papers of Iacono & Levinson (2008), Hunt et al. (2005), Wegener (2004), Verburg et al. (2004), Briassoulis (2000) are important references therefore.

The object being modeled with LUTI models is the urban system. It can be framed in seven subsystems depicted in Figure 1 (gray boxes). The natural environment, legal regulations, and infrastructures are the stage on which economic actors (persons) or actor groups (households, firms) perform their activities. The natural environment comprises all elements which would also exist without human beings. It is the basis for human activities and in itself an extremely complex subsystem. The anthropogenic parts — which result from human activity — of the urban system are embedded in the natural environment. The legal regulations and infrastructures are the result of societal decisions, e.g. voting on infrastructure projects or approval of land use plans. The actors' activities constitute the system of land use. Their patterns in space and time emerge from the decisions of the socio-economic actors when and where to perform an activity. The actors, or agents, consider the conditions of the underlying subsystems for their decisions. These modify again the conditions of the subsystems which means that feedback cycles are in place. The one between land use and transport is discussed in more detail below depicted in Figure 2.

The activities can be seen as decision chains (depicted as rhomboids). Not all decisions are taken equally often. Decisions related to travel are taken rather spontaneous every day whereas the decision on constructing a house is taken much less frequently. Even less frequent are group decisions, e.g. democratic decision processes. Hence, affected subsystems evolve with different speed. This has implications for the modeling and is discussed later. We can distinguish:

- Very slow processes like building infrastructures or modifying a land use plans
- Slow processes like construction of buildings

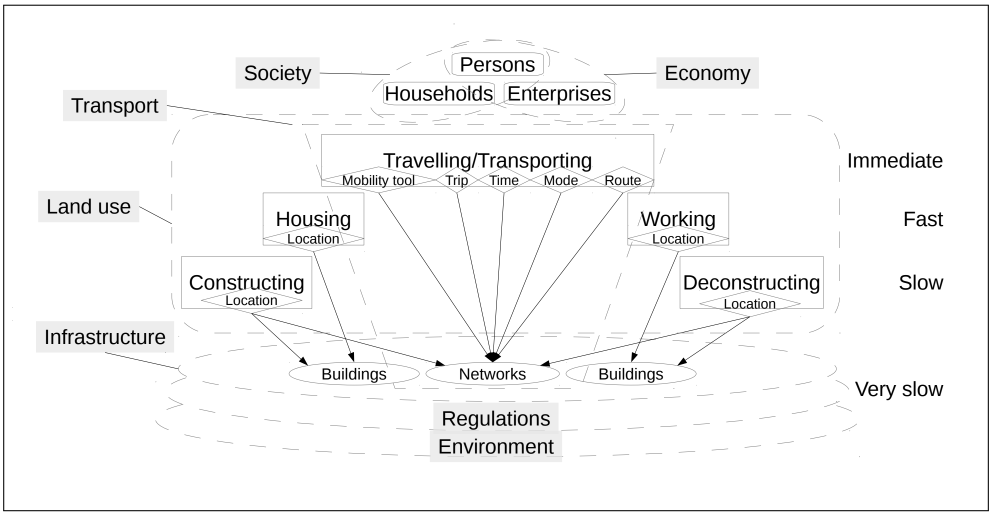

Figure 1: A framework of urban systems.

- Fast processes like location choice of households and firms
- Immediate processes like route choice decisions made on the road

The activities determine the evolution of the urban system. The resulting processes are related to each other, e.g. the construction of a new residential building gives households new possibilities to reside. However, not all processes are of the same kind. Some are decision processes while others are of a physical nature. Also the decision processes can be different. One example is the distinction of individual and collective decision making. An examples of the latter are discussed in the Chapters (?) of this book.inline]EPFL: Include cross ref to chapter 2.2 (Modeling real estate investment decisions in households) and 2.3 (Location choice models considering intra-household decisions)

In Figure 1 we can recognize two main parts of the anthropogenic urban system considered in LUTI models. The spatial distribution of activity places constitute the land use system. This system consists of specialized places which facilitate certain activities like housing, working or traveling. Since specialization often leads to spatial separation, traveling arises as necessity. From this point of view the transport system is the subsystem of land use which relates activity places with each other. Traveling persons and transported goods on transport networks constitute the transport system. The relevance of the transport system within the land use system is the feedback cycle shown in Figure 2.

A location's attractiveness depends on how easy it is to reach. Investors anticipate the attractiveness for potential users and are consequently producing new facilities in places with high accessibility. The newly provided facilities get eventually used by the inhabitants of the urban system. Since the performance of transport

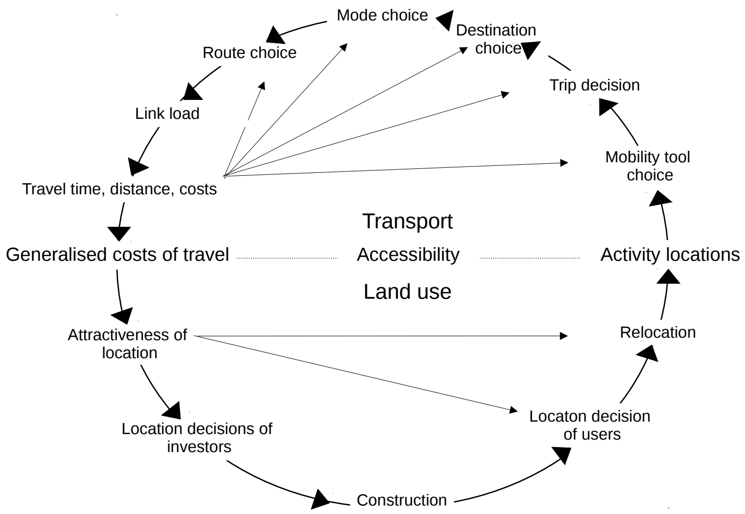

Figure 2: Feedback cycle between land use and transport systems adapted from Wegener & Fürst (1999).

infrastructures depends on capacity and usage, the attractiveness of a location may decrease if it is more frequently visited.

Accessibility is a central measure in this context. Generally, it is a measure of attractiveness of a location. However, there are various definitions in a number of fields (Geurs & van Wee 2004) which shows the generality of this concept. The important aspect in the context of LUTI models is that accessibility measures how opportunities / facilities are related via the transport network to one another. The accessibility measure used should thus be sensitive to variations in generalized travel costs and spatial distribution of facilities.

3 Modeling the urban system

A *model* is basically a simplification of reality (Gilbert & Troitzsch 1999). The researcher is the subject who perceives an object and thus creates a model of some form to get a hold of it. The term model is quite general and often more precise terms could be used. The researcher uses different tools for modeling. First of all his brain, but also language, pencils and computers. In analogy we find models in different formulations such as ideas, concepts, theories, physical replications, mathematical formulas or computer programs. These terms are associated to different levels of detail in the formulation of a model.

According to the subsystems and processes discussed before one can distinguish land use transport models and land use transport environment models. Most LUTI models presented here belong to the first category and focus on the feedback cycle between the two main components. LUTI models are land use change [1] models, which try to explain for what purpose a piece of land is *used*. The terms *interaction* and *change* show that the models do not aim at describing a solid state, but interdependent dynamics, i.e. evolution over time.

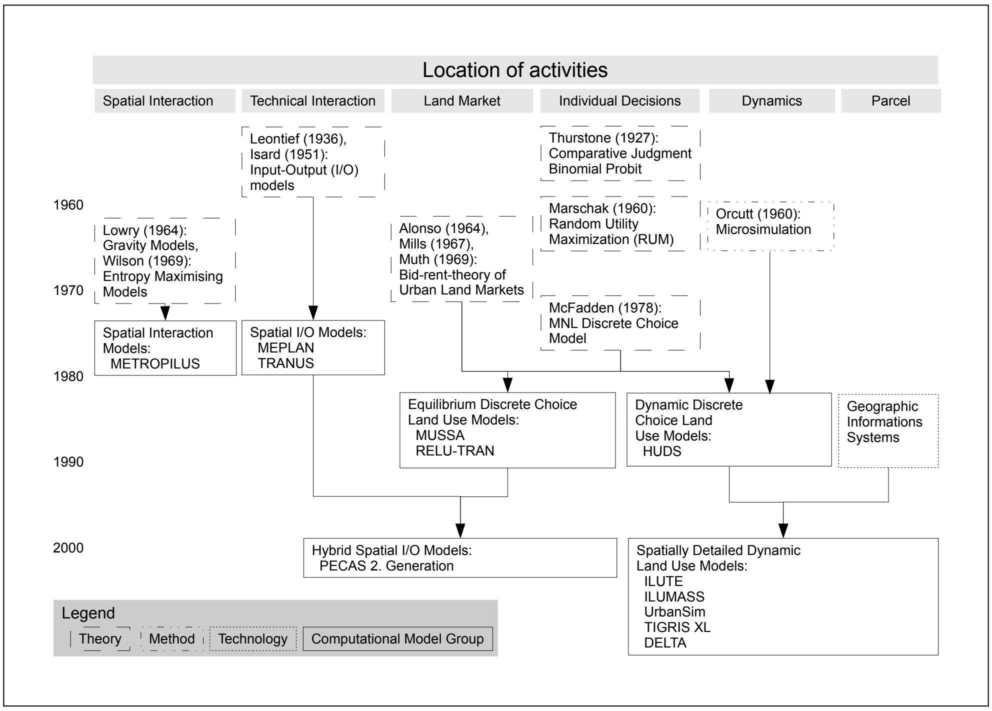

Figure 3: Systematics of LUTI models adapted from (Waddell 2005).

Figure 3 shows a systematics of LUTI models. The vertical axis is the time line. Aspects of reality which are reflected in the theories and models are distributed horizontally. The rectangles represent elements of different nature as indicated in the legend. An arrow symbolizes *influence*. Representative models of the respective group are shown with capital letters. Predecessor are not included to keep the figure concise.

We recognize four strands of theory which formulate the basic principles underlying LUTI models. The dynamics of the urban system was accounted for by using the method of microsimulation as "general approach to the study and use of models" (Orcutt 1960, p. 893). The use of parcels became possible through availability

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[1] Following the terminology of Briassoulis (2000)

of geographic information systems and the according data. Parcels are a meaningful geographic reference because they are the legal entities with highest spatial and regulatory detail.

We can also recognize three waves of development like they have been identified by (Iacono et al. 2008): (I) Spatial interaction and spatial input-output models came up in the sixties, (II) econometric models in the eighties and (III) spatially detailed microsimulation models at the end of the nineties. Each of the three waves has been triggered by theoretical and/or technological developments. The developments in economic theory in parallel with the increasing computational power and data availability lead to this development path.

The first LUTI model was implemented by Lowry (1964) on the basis of gravity theory. The theory was borrowed from physics and stated that the interaction of two regions is proportional to their size (in terms of jobs) and inversely proportional to the distance in between. This model was a start with more inductive than deductive strength.

These first models have been succeeded by econometric models in the eighties (second wave). This is the group of Spatial Computational General Equilibrium (SCGE) models. These work with representative agents (Table 2) and explain the interaction of regions based on markets where economic actors make their decisions. Hence, the empirical work required the analysis of more detailed data than aggregates per considered region. Observations of economic actors had to be collected therefore.

The next step followed with the development of discrete choice modeling by McFadden (1978, 1981) and the development of information technologies, which made microsimulation very attractive. HUDS (Harvard Urban Development Simulation) was the first large scale model using microsimulation (Kain 1985). HUDS has been followed by other projects like TLUMIP (Transportation and Land Use Model Integration Project) which further developed TRANUS (Weidner et al. 2007). From the project resulted the Land Use Scenario DevelopeR (LUSDR) (Gregor 2007). Further efforts lead to the development of PECAS (Hunt & Abraham 2003) and UrbanSim (Waddell 2002). This third wave was triggered by the combination of theoretical developments in discrete choice modeling, technical feasibility of microsimulation due to increasing computation power and social relevance because of pollution and climate debates. The model requirements include ever more ecological indicators like CO_2, land consumption, energy use and air pollution. Up to now LUTI models treat effects of the anthropogenic system on the natural environment to some extent. The feedback from the natural environment on the anthropogenic system is widely neglected. Coupling a climate model and considering reactions to climate change would be an example hereof.

4 Overview of LUTI models

This section provides a general overview of operational LUTI models built on Wegener (2004), Zöllig et al. (2011). We will only look at *operational* models. Operational LUTI models are calibrated for a specific region and ready to use for policy analysis. A non operational model might be existing as software or mathematical formulation but it is not yet applied to a specific area. The operationalisation alone can be a work-extensive project (Iacono & Levinson 2008, Gruber et al. 2000) and keeping it operational as well. The number of applications is a proxy for transferability to other locations which also shows usability and maturity to some extent.

Currently, a number of operational LUTI frameworks exist (Wegener 2004, Zöllig et al. 2011). We can identify two main groups with respect to the aggregation level. The first group, which is of main interest here, operates on the level of individual agents (Table 1). These models are also referred to as disaggregate/microsimulation models, multi agent systems (MAS) or agent-based models (ABM). The second group uses representative agents (Table 2). Therefore they are also denominated as aggregate models.

Model Name	**Place of Origin**	**Nb. of Applications**
UrbanSim[a]	Eugene, Oregon	> 1
TRESIS[b]	Sidney	
ILUMASS[c]	Dortmund	1
ILUTE[d]	Toronto	
TIGRIS XL[e]	The Netherlands	
PUMA[f]	The Northern Dutch Randstad	
LUSDR/TLUMIP[g]	Oregon	
STASA[h]	Stuttgart	

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[a] (Waddell 2000, 2002, Waddell & Ulfarsson 2004, Miller et al. 2005, OPUS User Guide 2011, UrbanSim Developers 2013)

[b] (Hensher & Ton 2002, Institute of Transport and Logistics Studies 2009)

[c] (Wagner & Wegener 2007, Beckmann et al. 2007, Strauch et al. 2005)

[d] (Salvini & Miller 2005, Miller et al. 2004, Miller & Salvini 2001)

[e] (Zondag 2007)

[f] (Ettema et al. 2007)

[g] (Gregor 2007, Weidner et al. 2007)

[h] (Haag 1990, Pumain & Haag 1991, STASA 2013)

Table 1: Overview of land use transport interaction models with multiple agents.

The reasons to use disaggregate models are (i) the ability to explain macro level phenomena from a micro level, (ii) the grounding in microeconomic theory (iii) the capability represent complex systems, (iv) flexibility with respect to result evaluation (aggregation levels) and (v) flexibility in accommodation different modeling approaches. However, the appropriateness of the model will always depend on the

Model Name	Place Of Origin	Nb. of Applications
RELU-TRAN[a]	Chicago	> 1
PECAS[b]	Oregon	
TRANUS[c]	Carracas	
DELTA[d]	London	
MUSSA[e]	Santiago	
MEPLAN[f]	Cambridge	
METROPILUS[g]	Ohio	
RURBAN[h]	Tokyo	
METROSCOPE[i]	Portland, Oregon	
BOYCE[j]	Chicago	
CUFM[k]	California	
POLIS[l]	San Francisco	
IMREL[m]	Stockholm	
LILT[n]	Leeds	
KIM[o]	Urbana, Illinois	

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[a] (Anas & Liu 2007)

[b] (Hunt & Abraham 2003, Abraham & Hunt 2007, Abraham et al. 2005)

[c] (Barra et al. 1984, MODELISTICA 2013)

[d] (Simmonds 1999, 2001, Simmonds & Feldman 2005, Bosredon et al. 2009)

[e] (Martinez 1997*a*, 1992, 1997*b*, 2000, Martínez & Donoso 2010)

[f] (Echenique et al. 1990, Abraham & Hunt 1999)

[g] (Putman 1996)

[h] (Miyamoto et al. 1996)

[i] (Metro Regional Government 2013)

[j] (Boyce & Zhang 1997, Boyce & Bar–Gera 2003)

[k] (Landis 1994, Landis & Zhang 1998*b*,*a*)

[l] (Caindec & Prastacos 1995)

[m] (Anderstig & Mattsson 1991)

[n] (Mackett 1991)

[o] (Kim et al. 1989, Rho & Kim 1989)

Table 2: Overview of land use transport interaction models with representative agents.

purpose it is used for.

The origins of the models are listed in the tables because the context of development is important given the data dependency of the models. The footnotes of the tables show the references starting with the principal one. Additional references are given for convenience and to show recent activity. Therefore, maintained websites are also included.

5 A comparative overview of ILUTE, ILUMASS, and UrbanSim

This section will give a comparative overview of the three model systems UrbanSim, ILUTE, and ILUMASS. The characteristics considered for the selection of these three model systems are their (i) microscopic nature, (ii) capability to interact with a micro simulated transport model, (iii) explicit representation of time (dynamics) and (iv) the representation of social and economic development. The frameworks are *microsimulation* models, which are able to model disaggregated entities such as parcels or persons.

A characterization of the three selected MAS is given in Table 3 for easier comparison. They also serve as structure which is followed in the subsequent descriptions of the three selected models. A general discussion of the characteristics follows hereafter. The notations are derived from Wegener (2004), Zöllig et al. (2011).

Study regions The number of applications gives an idea on the ease of application of the model. Some of them are applied once, i.e. for one study region such as ILUTE and ILUMASS. In contrast, UrbanSim has been applied several times to metropolitan areas world wide. UrbanSim is probably the most frequently used microsimulation model. However, the ease of application is also very dependent on data availability and data requirements.

Comprehensiveness The comprehensiveness is shown separately in Table 4. The first part of the table shows the comprehensiveness with respect to real world subsystems, as presented in the framework in Section 2. The second part represents the detail with which processes and their interactions are considered. The possible detail in both components is related. E.g. preferences of households for upper level living units can only be considered if this information is available in the representation of the building stock.

Modeled Sub-systems What we denominated as society[2] in our framework is modeled as a population of persons. The models also exhibit the structure in the population to some extent. Gender, age, income and household structure are often considered. The endowment with mobility tools and social networks are less frequently considered despite their importance regarding travel behavior. The economy is represented together with jobs and firms. Again the models differ in the degree of detail in the sense that some represent the structuring of jobs in firms and others do not. In the models the land use sub-system is the outcome of location choices for activities. The available alternatives are buildings/facilities. Thus it is evident that buildings are prerequisites with respect to final activity locations. The transport

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[2] The meaning of the term is very broad and it is thus evident that the models' representation are minimalistic compared to the object in the real world.

Criteria	**UrbanSim**	**ILUTE**	**ILUMASS**
Purpose	Assist regional planning at local and state level	Experimental tool for investigating practicability of microsimulation	Develop fully model of microscopic land use, transport and environment
Study regions	world wide	Toronto (Canada)	Dortmund (Germany)
Theoretical Foundation			
Decision rule	RUM	RUM	RUM
Speed of equilibration	lag possible	lag possible	lag possible
Perception	full	asymetric	asymetric
Resolution			
Spatial resolution	grid cells, zones, parcels	grid cells, zones, parcels	grid cells
Temporal resolution	annual	flexible, depending on simulated subsystem	annual
Functioning			
Scope of equilibrium	partial	partial	partial
Simulation of time	iterative	iterative	iterative
Model structure	composite	composite	composite
Transport model	microsimulation	microsimulation	microsimulation
Modelling concept	hybrid	hybrid	hybrid
Usability			
Calibration technique	statistical	statistical	statistical
Calibration scope	model	sub-model	sub-model
Data requirements	micro objects, observed behaviour	micro objects, observed behaviour	micro objects, observed behaviour

Table 3: Characterization and comparison of selected LUTI models. This table is built on (Wegener 2004, Zöllig et al. 2011)

network is another important infrastructure in the context of transport planning. It is used to calculate more realistic impedances between activity locations which avoids using approximations such as euclidean distances. Regulations are introduced to the model as constraints. An example on the land use side are development constraints which make sure that no residential building is located on a site dedicated for agricultural use. The representation of the environment is reduced to aspects which are found to be influential with respect to modeled decisions. An example is the representation of green spaces or lake view which increase a locations' attractiveness for

Criteria	**UrbanSim**	**ILUTE**	**ILUMASS**
Sub-systems			
Persons, households, cliques	yes, yes, no	yes, yes, yes	yes, yes, no
Jobs, firms	yes, yes	yes, yes	yes, yes
Land use	yes	yes	yes
Network, buildings	exogenous, yes	yes, yes	yes, yes
Regulations	yes	yes	yes
Environment	no	no	yes
Processes			
Demography	yes	yes	yes
Firmography	yes	yes	yes
Housing	yes	yes	yes
Working	yes	yes	yes
Travelling	exogenous	yes	yes
Transporting	exogenous	yes	yes
Constructing	yes	yes	yes

Table 4: Comprehensiveness of selected LUTI models. The table builds on Wegener (2004), Zöllig et al. (2011)

housing.

Processes The selected models consider all processes distinguished in our framework. An exception is UrbanSim which relies on external transport models. The LUTI models differ in the modeling of the processes constituting the development of the urban system. Some processes are captured by modeling discrete decisions, others are transition models which update certain quantities on the basis of assumed rates. Discrete choice models capture the decision behavior (decision rules and preferences) of the represented actors. These are especially suitable to model markets of discrete goods. Consequently, the theory can be applied to location choice of activities, to travel and transport demand, construction and some parts of demography. In the last case we think of choice of partners.

There are currently no models which model the modification of regulations and ecosystems. Given the complexity of these processes it is reasonable to work with assumptions.

Theoretical foundations The selected urban simulation models are based on discrete choice theory (Domencich & McFadden 1975), which is used to model the demand side of markets in which goods such as jobs, land, housing or transport services are traded. The usual assumption for the decision rule is *random utility maximization (RUM)*. We also find different assumptions about the speed of equilibration in the modeled markets. The models presented in Table 3 also allow independent model variables, such as supply and demand, to adjust to equilibrium with some delay. The equilibration process takes multiple time steps in such cases. Microsimulation models can vary in the assumptions about the agents' perception of their environment. In Urbansim it is assumed that market participants have full information. In ILUTE and ILUMASS the information is assumed to be asymmetric in the markets, i.e agents have individual knowledge and search spaces.

Resolution The table shows the supported spatial units of the respective model and the temporal resolution in terms of a typical simulation period. The temporal resolution is one aspect of discrete simulation of time. The temporal resolution is given on a yearly basis in UrbanSim and ILUMASS. ILUTE allows to specify the scale of a simulation period.

Functioning In all three models a *partial* equilibrium is calculated, i.e. equilibrium is computed separately for each sub-market. This is a fundamental difference to models calculating a general equilibrium such as the afore mentioned SCGE models. Lagged equilibration is also possible if partial equilibrium is calculated.

Dynamic models represent time explicitly which allows to investigate the speed of effects. Thus dynamic models show the development of the system over time. A dynamic model allows for example to give evidence on the time frame which has to be expected for an desired transformation. Such analysis is not possible with cross sectional models. The selected models are simulating the evolution of the urban system over time by calculating a sequence of time steps. The modelers discretized the evolution and calculate cross sections of the system in an *iterative* way.

The *model structure* of each framework is classified as *composite*. This means that they consist of loosely coupled submodels, where each submodels has its own independent internal structure (Wegener 2004). A composite structure allows to integrate different model types.

All selected models include or are able to be coupled with a *microsimulation* transport model.

The *modeling concept* distinguishes between input-output-Models (I/O-Models) or multi-agent-systems (MAS). If both concepts are combined, the model is called *hybrid* (Zöllig et al. 2011). I/O-Models formulate relations between areal units on an aggregate level. MAS explicitly simulate these relations via the behavior of agents in space.

Usability All models are *calibrated* with *statistical* methods on the level of sub models. An approach to calibrate the overall model is only shown for UrbanSim to the authors knowledge (Ševčíková et al. 2007). A possible drawback of microsimulation models are the extensive data requirements. The modeler needs data for the base year which describe the starting point and data about the behavior of modeled agents. The latter can be derived from surveys or observations of real world behavior, e.g. route choices can be inferred from GPS data. In many situations, however, it is possible to get a first model from reduced and partially heuristic data sets, which can be extended later if the need arises.

The following sections provide a comprehensive description for each selected model. UrbanSim is selected as reference since it is used in the case studies presented in Chapters (?,?,?).inline]EPFL: Insert cross refs to case study chapters.

6 ILUTE

ILUTE (Integrated Land Use, Transportation and Environment; Miller & Salvini 2001, Miller et al. 2004, Salvini & Miller 2005) is an integrated, activity-based, microsimulation urban modeling system developed by a consortium of Canadian researchers. ILUTE is built as an experimental tool with the main research objective to investigate to which extent microsimulation can be implemented within a practical model. ILUTE has been applied for the greater Toronto and Hamilton area.

6.1 Main components and structure

Four contiguous main components represent the heart of ILUTE; a land use, location choice, auto ownership and an activity and travel component.

The conceptional design of ILUTE is strongly influenced by the object-oriented software development paradigm. It aims to map objects ("agents") from the real world into the microsimulation model and simulates their activities and interaction. Objects in ILUTE include persons, transportation networks, the built environment, firms, the economy and the job market.

Market demand and supply interactions are simulated in a disaggregate fashion by a disequilibrium based microsimulation modeling framework for the built space markets (Farooq & Miller 2011). The purchase of a house or car, but also the choice of a spouse or the decision to select a job are considered as market interactions. They have in common that consumers and suppliers interact in a market and try to maximize their individual utility and profit levels. As in the real world consumers and suppliers are assumed to have limited information about the market, e.g. a buyer will not be able to evaluate the entire house market.

The system has been extended for emission modeling to calculate and assess transport introduced air pollution (Hatzopoulou & Miller 2010). A recent effort integrates MATSim to obtain a finer resolution for emission modeling (Hao et al. 2010). A comprehensive description of MATSim is given in Chapter (?). inline]EPFL: Include ref to Chapter 3.2

Multiple temporal and spatial resolutions are supported. In real urban systems time and decision processes are continuous processes that need to be discretized in the modeling system. To simulate change processes of different urban subsystems with different speeds, such as the housing market or transportation infrastructure changes, timestamps are used that are attached to each object. They allow to update and execute an object with its optimal temporal frequency at a flexible time. This is, several levels of temporal aggregation can coexist in ILUTE. Furthermore, different spatial aggregations such as buildings (as a container for activities), parcels, zones (census tracts, traffic zones), planning districts and grid squares are supported.

The Travel Activity Scheduler for Household Agents (TASHA) represents the conceptual core of ILUTE (Miller & Roorda 2003, Roorda et al. 2009). It is a microsimulation model that generates activity schedules and the resulting travel pattern for every person of a household. The implementation of TASHA is based on three assumptions (Miller & Roorda 2003, pp. 4):

- "[...] scheduling is an event-driven, sequential process [...]"
- "[...] activity/travel scheduling is not an optimizing procedure." This means that the resulting schedule might be sub optimal.
- "[...] travel mode choice (and the associated allocation of household vehicles for individual person travel, as required) is inherent in the activity scheduling process."

Activities are often connected and require the coordination of multiple participants. In ILUTE activities are called projects. A project is defined as a coordinated set of activities that belong together to achieve a common goal (Axhausen 1998). They are used as containers to schedule coordinated joint activities such as work, school, shopping or home-based activities, e.g. when parents are taking care of their children.

An activity scheduling and mode choice component of TASHA creates activity schedules and travel pattern for each person in a household (Miller & Roorda 2003). The activity scheduling follows a set of rules, according to a predefined priority order, to organize activities into projects. Based on this, schedules for interacting household members are built. This includes: (i) the generation of activities based on observed joint probability distributions for all persons, (ii) the organization of these activities into project agendas, i.e. into a pool of activities, and (iii) the creation of individual schedules built from the project agenda while taking spatio-temporal constraints into account (Roorda et al. 2009). The mode choice component assigns a transport mode by using a tour based random utility mode choice model that maximizes the overall household utility (Roorda et al. 2009); e.g. in case of overlapping tours of at least two household members, the vehicle is assigned to the person that would get the highest disutility by using another mode.

6.2 Key features

A key feature of ILUTE is the representation of compound groups such as (i) households and families, including family relationships as father, mother, spouse and exspouse, children and siblings, (ii) businesses and establishments as well as (iii) any collaborating persons that do not belong to the same household.

As in the real-world, in ILUTE decisions can be made by individual persons, or by collectives in compound groups. Individual persons (agents) can take several roles: a person can be a worker, a parent and a property owner at the same time, and has to take a variety of decisions. In compound groups, location choice and activity scheduling decisions can be traced back to this entity level that provides revealing insights for researchers. An abstraction from real-world entities has been made for businesses (firms), which can take own decisions and not as a collaborative decision process of employees or firm members. To capture object behaviors, modeling methods such as state transition, random utility, rule-based, learning, exploration and hybrid models are implemented.

Complex decision processes in ILUTE are managed by an flexible and extensible mechanism (Salvini & Miller 2005):

- A time-proxy decision process allows objects to handle future events such as the purchase of an uncompleted dwelling. This allows anticipatory behavior. This means to make decisions based on speculations. For instance, a family might move into a larger dwelling when they expect offspring.
- ILUTE provides mechanisms to trigger events that are not based on a single stimulus but rather on multiple state changes as a whole. In this context the term stress is used to characterize changes of the current state of a person. Stress occurs if, for instance, the state deviates from a desired, expected or optimal state. The concept of stress is based on a utility based framework. If the stress level reaches a certain level, the stress manager tries to resolve stress by using multiple mechanisms. If, for instance, a long commute causes a serious stress level, this can be resolved by moving into a new home, changing the work place or switching between available transport modes. The stress manager allows to handle triggered events, joint decisions, accumulated stress and household interactions.

ILUTE is capable of capturing and tracking complex interactions of the urban system such as activities and behaviors of individual objects, which allows detailed insights for transportation, housing and urban policies analysis. Therefore, each object in ILUTE has its own, unique representation (perception) of reality. In order to simulate this, an object carries (stores) its knowledge about itself and its environment. The absence of perfect information, e.g. of the road network of a city, is realized by artificially adjusting the access to the true system state, which for performance reasons is only stored once.

6.3 Data requirements and preparation

ILUTE provides extensive data synthesis procedures to synthesize households and persons, buildings and dwelling units, the mapping of households to dwellings and the mapping to work. Moreover, it enables researchers to trace individuals and to analyze their cumulative effects. To capture complex urban change processes, resulting spatio-temporal data can be visualized in 3D by Houdini 3D from Side Effects Software (Salvini & Miller 2005, Side Effects Software Inc. 2013), a professional animation tool.

7 ILUMASS

The ILUMASS project (Integrated Land Use Modeling and Transportation System Simulation) (Strauch et al. 2005, Beckmann et al. 2007, Wagner & Wegener 2007) was under development between 2002 and 2006 by an interdisciplinary consortium of German research institutions. The main purpose of the ILUMASS project was to develop a fully microscopic integrated land use, transport and environment (LTE) model that helps to explore feasible and successful policies and to achieve sustainable urban transport. ILUMASS has been developed and applied for the urban region of Dortmund, Germany, including the city of Dortmund and 25 surrounding municipalities.

7.1 Main components and structure

The three microscopic LTE modules are the main components of ILUMASS. Each module consists of several loosely coupled microscopic sub models with their own independent internal structure. This allows to capture changes in land use, its impact on activity behavior and transport demand and the effects of transport and land use on the environment. A comprehensive description is given in (Strauch et al. 2005, Wagner & Wegener 2007). At this point a brief overview is provided:

The *land use module* is built on an existing macroscopic urban simulation model of the Dortmund region developed at the University of Dortmund. This is the IRPUD model (Wegener 1982*b*,*a*, 1994, 2004). Its macroscopic modules were reimplemented for ILUMASS in microscopic form. The microscopic land use model consists of the following sub models (Strauch et al. 2005):

- Population: The population model simulates the demographic development of households and persons. This includes the aging of persons, the establishment of new household and their growth, decrease and dissolution over time, e.g. when children are born or a member dies or separates. Also changes in employment are modeled.

- Firms: The firmography, describing the demography of firms, works analogously to the population model. Firms can be founded, they can grow or decline and can be closed.

- Residential mobility: The residential mobility model models location choice decisions of households such as immigration, emigration or just relocation within a region. Relocation decisions are based on the attractiveness of a dwelling. This includes the attractiveness of a location, quality and rent in dependence to the housing income. A household accepts a new dwelling if it is significantly more attractive than the current dwelling.

- Firm location: Location choice decisions of firms are based on accessibility, size, price, quality and image. A firm that is unsatisfied with its current location checks out up to ten alternative locations and moves if a selected location provides significant improvements.
- Residential buildings: The residential development model demolishes, upgrades or builds new buildings for rent or sale.
- Non-Residential buildings: The non-residential development model examines the demand of floor space per zone. If one zone has a low vacancy rate, new floor space is developed. Floor space is subject to land use constraints by municipal land use plans.

Updated locations are provided to the transport model.

The transport module is a detailed agent-based model. It models daily activity pattern, the resulting travel demand and goods movement. For each hour of the day a separate origin destination (OD) matrix is computed. Traffic flows, link loads and travel times are computed by a dynamic traffic assignment model. A psychological actor model computes a weekly activity plan for each person by considering 29 different activities. These are grouped in 4 main categories such as personal, job and school, social activities and leisure. If an activity is placed outside home, a place, a travel mode and the departure time are selected. When picking a place, the capacity limit of the activity location is taken into account. Routes are computed on shortest paths, iterating through all person until an equilibrium is reached. The goods transport module assigns good flows between companies in the study region. Therefore it takes a macroscopic input-output matrix of the German economy and a German survey on goods transport as input. The generated demand is used in the microscopic travel simulation described above.

The environment module uses travel times, flows and speeds from the transport model as input, and determines greenhouse gas emissions, air pollution, traffic noise, barrier effects of traffic and also visual impairments caused by transport and emissions (Strauch et al. 2005).

Each sub module is independent and self executable. The coordination of the simulation procedure and the interaction among the various sub models is managed by a dedicated software component. It executes the modules sequentially and waits with the execution of the next model until required results are calculated by previous modules. The data exchange among the sub models is realized via an integrated database. The data is disaggregated into raster cells of $100m \times 100m$ size. The evolution from the base year data is simulated in annual steps.

7.2 Key features

The project contributed to the state-of-the-art in integrated LTE modeling by incorporating three fully microscopic modules for urban land use, transport, and the environment. Distinct features of ILUMASS are the fully microscopic implementation and the consideration of the environment feedback to land use. Shortcomings were found in previous LUTI models in terms of too aggregate temporal and spatial resolutions in order to model sustainable urban transport (Strauch et al. 2005). The latter issue is accounted for by including environmental factors such as clean air or noise in location choice decisions of households and firms (Strauch et al. 2005).

The designers introduce activity patterns in the course of a microscopic implementation of a travel demand model. This is found to be necessary to consider trip chains (multipurpose uni- and intermodal), trips for each hour of a day, the linkage between activity and mobility patterns of household members, emerging lifestyles and work patterns, the interdependencies between travel demand and car ownership as well as residential and firm location, and also between land use and built form and mobility behavior. This is found to be necessary to overcome issues originating in too aggregate temporal and spatial resolution.

7.3 Data requirements and preparation

The base year data incorporates synthetic "populations" of households, businesses, buildings for residential, commercial and public use, vehicles as well as the road and public transport networks (Moeckel et al. 2003, Strauch et al. 2005). (Moeckel et al. 2003) presents the approach, used in ILUMASS, to generate a synthetic population that is statistically equivalent to a real population.

Households: The synthetic population includes households with individual household members. Households are characterized by household size, income, number of cars, ownership of a monthly season ticket, a car sharing membership and address. Each person is described by age, gender, education, employment status, driving licence ownership and income.

Firms: Businesses also include public facilities such as schools, hospitals or museums. They represent the employers and are specified by industry, number and qualification of employers, their capacity to serve customers, the number and type of vehicles and their location.

Buildings: Attributes of residential buildings are the building type, e.g. single or multi family residential housing, size, quality, tenure and price. The buildings for commercial and public use are described by available and used floorspace for industry, retail, office and public use as well as the price.

8 UrbanSim

UrbanSim (Waddell 2000, 2002, Waddell & Ulfarsson 2004, Miller et al. 2005, OPUS User Guide 2011) is an extensible, agent-based urban simulation model developed by Paul Waddell and his team, first at the University of Washington, Seattle, later at the University of California, Berkeley. UrbanSim was initially developed in 1996 as part of the Transportation and Land Use Model Integration Project (TLUMIP) initiated by the Oregon Department of Transportation (Waddell 2002). In 2005 UrbanSim was reimplemented as part of the open platform for urban simulation (OPUS). In the following, no distinction between UrbanSim and OPUS is made for simplification.

UrbanSim aims at simulating interactions between land use, transportation, economy and the environment at large-scale metropolitan areas and over a long time span, typically 20–30 years. The motivation for UrbanSim is to assist integrated 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 2002). It is designed to explore and analyze the effects of policies at a disaggregated level as a scenario evaluation system (Waddell 2011). It is intended to support modelers and decision makers in government. UrbanSim has been applied for several metropolitan areas such as the Puget Sound Region, the San Fransisco Bay Area and currently, as part of the SustainCity project, the canton of Zurich, the greater Brussels area and Île de France.

8.1 Main components and structure

UrbanSim is not a single model, rather it is a tool for the integration of several models aimed at the simulation of urban development. UrbanSim mainly consists of six models reflecting the decisions of households, businesses, developers and governments (as policy inputs) as well as their interactions in the real estate market (Waddell 2002). The responsible models are the Econometric and Demographic Transition Models, the Household and Employment Mobility Models, the Household and Employment Location Models, the Real Estate Development Model, and the Real Estate Price Model. Econometric and Demographic Transition Models as well as Household and Employment models are independent models; in this chapter these are presented coherently for simplification.

UrbanSim does not model transport itself. To update traffic conditions it relies on the interaction with external transport models (Wegener 2004). As part of the SustainCity project MATSim, an agent-based travel model, and METROPOLIS, a dynamic transport model, are integrated with UrbanSim – detailed descriptions are given in Chapter (?) and (?) respectively. inline]EPFL: Insert references to transport model sections 3.2 and 3.3. Moreover, external macroeconomic models can be integrated. The scheduling and implementation of events, meaning read and write access to the database, of these individual model components is managed by a coordinator module.

The UrbanSim models are described in the following according to their processing sequence during the simulation. The sequence of model calls does not necessarily indicate an interaction between contiguous models. A comprehensive model description is provided in (Waddell 2002, 2000):

Accessibility Model: The Accessibility Model is the linkage between land use and transport. It takes the output data provided by the external travel model and maintains accessibility pattern for the internal UrbanSim models. Models that make use of travel model output are the Household and Employment Location Models as well as the Real Estate Price Model.

Econometric and Demographic Transition Models: The Demographic Transition Model simulates births and deaths in the population. These can be specified by providing population control totals, e.g. by income groups or age. Analogous, the Econometric Transition Model simulates the creations and losses of jobs. New created households and jobs have no location. The location assignment follows later by the household and employment location choice models.

Household and Employment Mobility Models (relocation models): These models simulate whether households or jobs relocates. Such households or jobs are placed in a queue and receive a new location from the location choice models which are described next. If a household or job decides to move their current location becomes vacant. Thus, they change the real estate vacancies conditions, which are used in the real estate development and price model.

Household and Employment Location Models: These models select, in a three step process, a location for each household and job that have no current location. For households, first a random sample of vacant residential units is selected. In the second step the selected units are evaluated for their desirability by a multinominal logit (MNL) model based on the variables and estimated coefficients included in Household Location Choice Model (HLCM). Finally, households pick their most desired location. The Employment Location Choice Model (ELCM) approach is very similar; only the new location of a job is selected randomly among the alternative locations of the random sample.

Real Estate Development Model (developer model): Developer decisions such as new construction, renovation and reconstruction of existing structures as well as the type of development is simulated by the Real Estate Development Model (REDM). It considers all geographical units of analysis (GUA), e.g. grid cells, for which development is allowed. Each GUA is evaluated by a multinominal logit model for possible development types, including the alternative of no development.

Real Estate Price Model: The Real Estate Price Model (REPM) predicts the prices of each property or GUA based on location characteristics, such as neighborhood accessibility and policy effects. The resulting land values are used as input in the next UrbanSim iteration in the Household and Employment Location Models and the Real Estate Development Model.

8.2 Key features

OPUS is a framework for urban land use, transport and environmental modeling and aims to provide a shared platform that can be easily extended by developers or users and adapted for different applications (Miller et al. 2005). Therefore, the software is released as open source software under the GNU General Public License (GPL) (Miller et al. 2005). The implementation and maintenance burden of a model infrastructure is taken by OPUS. This approach enables developers and users to focus on experimenting with and applying models (Miller et al. 2005). Furthermore, OPUS provides an integration of model estimation that allows to keep the model specification consistent between estimation and simulation runs.

The system is easily extensible either by creating an individual OPUS package or by coupling external models via dedicated interfaces (Miller et al. 2005). This approach eliminates several sources of inefficiencies and inconsistencies such as implementing complex data exchange methods, handling incompatible data formats and software languages or facing problems to access internal algorithms when coupling external models or adding new OPUS packages (Miller et al. 2005).

A particular focus of the OPUS framework lies on the computational performance. It is implemented in Python and takes advantage of high performance C and C++ libraries (Waddell 2011, Miller et al. 2005) . Another important aspect of the OPUS software is the usability by a wide group of users and modelers without a profound expertise in software development by providing a graphical user interface (GUI) (Waddell 2011). UrbanSim provides various visualization techniques to present model inputs, processes and simulation results as charts and colored static or animated 2D maps (Miller et al. 2005, Vanegas et al. 2009).

Currently, UrbanSim supports three different geographic units of analysis (GUA) (OPUS User Guide 2011) (pp.93). These are parcels, zones and grid cells with a configurable resolution. The UrbanSim models simulate the evolution of the data store in annual steps (Waddell 2002).

8.3 Data requirements and preparation

The input to the UrbanSim models includes the base year data, access indicators from the external travel model, and control totals derived from external macroeconomic forecast models. In UrbanSim the base year data store contains the initial state of a scenario (Waddell 2002). It represents chosen attributes of persons, jobs, real estate and locations and the mapping among these attributes (Waddell 2002). Typically the database includes (i) geographies, initial (ii) household and (iii) job information for a given base year. The geographic layer represents administrative boundaries. Households are represented as individual objects including requisite attributes in order to model location choice decisions. Persons are attached to households and exhibit attributes relevant in terms of travel behavior. Finally, the database includes job entries, incorporating the employment sector, representing employment

(Waddell 2002). The primary sources of the base year data are usually surveys or censuses.

If disaggregate information is not available, the population synthesizer in OPUS can be used. The included synthesizer is a snapshot of the PopGen algorithm developed under the SimTRAVEL research initiative (Ye et al. 2009).

9 Conclusions

The goal of this chapter is to assess the state of the art of land use transport interaction models, with a focus on agent-based models. To achieve this goal we presented an introduction to the subject, and an overview of operational models on the basis of original and review papers. The overview includes aggregated models as well for completeness and reference. Thereafter we focused on disaggregated models because of (i) the ability to explain macro level phenomena from a micro level, (ii) the grounding in microeconomic theory and (iii) the capability to represent the evolution of complex systems like cities. A more detailed discussion about added value of microsimulation follows in the next chapter. inline]EPFL: Check if the second chapter is about microsimulation.

Three agent-based models, ILUTE, ILUMASS, and UrbanSim, are considered in more detail. The comparison reveals that even though the purpose of all systems is generally the same, they have different emphases/strengths:

ILUTE is the most detailed system available today, especially in considering interdependencies and structures within society. The aim of the developers to research the practicability of microsimulation approach is recognized.

ILUMASS considers the role of the natural environmental most. The system incorporates explicitly some feedback between land use and the natural environment.

UrbanSim is designed as an open platform for urban simulation. This makes the model flexible, expandable and easily available. UrbanSim includes important tools with respect to practical application such as a graphical user interface, estimation capabilities, data synthesizer, calibration and evaluation tools and interfaces to various transport models as well as data storages. This approach makes UrbanSim attractive for the application in other regions. Therefore, it is today probably the most frequently used microsimulation land use transport interaction model.

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