MATSIM FOR URBANSIM

Integrating an urban simulation model with a travel model

vorgelegt von

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der Technischen Universität Berlin
zur Erlangung des akademischen Grades

Doktor der Ingenieurwissenschaften
– Dr.-Ing.–

genehmigte Dissertation

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Tag der wissenschaftlichen Aussprache: 23. Juli 2013

Berlin 2013
D 83

ABSTRACT

Land use and transport interaction (LUTI) models allow to perform impact analysis and the evaluation of transport, land use and environmental policies. The use of state-of-the-art LUTI models is valuable to decision makers in assessing alternative combinations of transport, economic, and environmental policies, and investments in specific metropolitan areas in order to attain their social, economic and environmental objectives.

LUTI models can be seen as simplifications of the urban system. They try to represent the urban system, with all its processes and interactions as well as its evolution over time. In particular, LUTI models are taking the feedback cycle between land use and transport into account. Both land use and transport are influencing each other in a dynamic and complex manner. Accessibility provided by transport influences location decisions of developers, firms and households. Conversely, land use determines the need for spatial interaction. The main purpose of LUTI models is to understand the interactions between land use and transport and consequently to use the knowledge to explain effects of modifications to the urban system such as modifications on the structure of the transport system, the land use patterns and the environment.

Accessibility is a central measure. Generally, it is a measure of attractiveness. The important aspect in the context of LUTI models is that accessibility measures how opportunities, e.g., workplaces, locations for shopping and leisure, are linked with each other via the transport network and how well they can be reached. Various accessibility measurements exist. One example is the so-called logsum that is used as a policy evaluation measure. It is an utility-based measurement of accessibility reflecting the (economic) benefit, as the maximum expected utility, that someone gains from access to spatially distributed opportunities.

So far, modern operational models taking the feedback cycle between land use and transport into account are still missing or are not implemented in a consistent way. This dissertation aims to address this issue by integrating the micro-simulation land use model UrbanSim with the agent-based travel model MATSim. UrbanSim is an extensible agent-based urban simulation model that aims at simulating interactions between land use, transportation, economy and the environment at large-scale metropolitan areas and over long time horizons. MATSim (Mutli-Agent Transport Simulation) is a disaggregated agent-based transport model that is designed to simulate several million travelers individually for large real-world transport scenarios.

This dissertation presents concepts and implementation details (i) to couple both frameworks directly at a microscopic person-centric level. Moreover, the robustness of the software integration is taken into account by using a "certified grammar" (XSD) to validate the data exchange. The computational efficiency of the traffic simulation is increased by the so-called warm and hot start that reduces computing times of simulation runs. (ii) Both, the integrated modeling framework and the impact of a large accessibility increase are analyzed in case study. (iii) The traffic model is extended to compute accessibilities at high resolutions. The proposed approach is computationally feasible and provides a spatially differentiated picture; artifacts such as supposedly homogeneous accessibility within zones are removed.

ZUSAMMENFASSUNG

Integrierte Landnutzungs- und Verkehrsmodelle, sog. Land use and transport interaction (LUTI) models, ermöglichen Analysen und Bewertungen von Verkehrs-, Landnutzungs- und Umweltmaßnahmen. Sie dienen politischen Entscheidungsträgern als Unterstützungswerkzeug um alternative Verkehrs-, Wirtschafts- und Umweltmaßnahmen, sowie Investitionen in bestimmte Regionen zu beurteilen und soziale, wirtschaftliche und ökologische Zielsetzungen gezielter umsetzen.

LUTI Modelle können als vereinfachte Abbildung des urbanen Systems – mit all seinen Prozessen und Wechselbeziehungen – angesehen werden. Charakteristisch für LUTI Modelle ist der Rückkopplungsprozess zwischen Landnutzung und Verkehr. Ziel ist die Wechselwirkung zwischen beiden Teilsystemen zu verstehen und Auswirkungen durch Modifikationen an diesen Teilsystemen erklären und prognostizieren zu können. Landnutzung und Verkehr beeinflussen sich auf eine dynamische und komplexe Weise. Die Erreichbarkeit von Aktivitätenorten, d.h. von Arbeitsplätzen, Einkaufs- und Freizeitgelegenheiten, beeinflusst Standortentscheidungen sozioökonomischer Gruppen (Haushalte, Firmen und Bauunternehmen). Umgekehrt ergibt sich durch die Verteilung der Aktivitätenorte die Notwendigkeit räumlicher Interaktion. In diesem Kontext ist die Erreichbarkeit ein zentrales Maß und spiegelt die Attraktivität von Aktivitätenorten wieder und zeigt wie gut Aktivitätenorte über das Verkehrssystem verbunden sind und erreicht werden können. Ein Beispiel der Vielzahl von Erreichbarkeitsmaßen ist der sog. "Logsum Term", der zur Evaluierung von Richtlinien verwendet wird. Er ist ein nutzenbasiertes Erreichbarkeitsmaß und spiegelt den maximal zu erwartenden ökonomischen Nutzen einer Person wieder, den diese durch Zugang zu räumlich verteilten Aktivitätenorten erlangt.

Bisher fehlen einsatzfähige Modelle, die den Rückkopplungsprozess zwischen Landnutzung und Verkehr berücksichtigen oder deren Modelle konsistent integrieren. Ziel der Dissertation ist es, dieser Problemstellung nachzugehen und moderne agentenbasierte Microsimulationsmodelle, UrbanSim und MATSim miteinander zu koppeln. UrbanSim ist ein flexibles Landnutzungsmodell, das Wechselwirkungen zwischen Landnutzung, Verkehr, Wirtschaft und Umwelt für große Metropolregionen und über lange Zeithorizonte simuliert. MATSim (Multi-Agent Transport Simulation) ist ein mikroskopisches agentenbasiertes Verkehrsmodell zur Simulation umfangreicher Verkehrsszenarien mit mehreren Millionen individuellen Verkehrsteilnehmern.

Diese Arbeit stellt Konzepte und Implementierungsdetails zur (i) mikroskopisch personenzentrierten Kopplung beider Simulationsmodelle vor. Die Robustheit der Software-Anbindung wird durch die Validierung des Datenaustausches über eine Metasprache (XSDs) erreicht. Zur Laufzeitoptimierung der Verkehrssimulation wird ein sog. Warm- und Hot-Start implementiert. (ii) Das integrierte Simulationsmodell wird in einer Fallstudie untersucht – dabei wird die Erreichbarkeit eines schlecht angebundenen Gebietes drastisch verbessert. (iii) Zudem wird das Verkehrsmodell um eine Komponente zur effizienten Berechnung hochauflösender Erreichbarkeiten erweitert. Der vorgestellte Ansatz bietet ein differenziertes Bild von Erreichbarkeiten im Raum. Artefakte, wie vermeintlich homogene Erreichbarkeiten in Zonen, entstehen nicht.

ACKNOWLEDGMENTS

I would like to take the opportunity to thank all those who supported me during my dissertation.

Especially, I would like to thank my supervisor Kai Nagel for his support and patience on the way to my doctoral thesis. I would also like to thank Constantinos Antoniou for kindly agreeing to be my second advisor.

There are many people who contributed to this work through outstanding scientic collaborations and inspiring discussions. I would like to thank Paul Waddell, Liming Wang, Christof Zöllig Renner, Johannes Illenberger, Michael Zilske, Marcel Rieser, Michael Balmer, Michel Bierlaire, Kirill Müller, Dimitrios Efthymiou, Theresa Thunig, Dominik Ziemke and Daniel Hosse.

This work was funded in part by the European Union Seventh Framework Programme (FP7) within the project "Micro-simulation for the prospective of sustainable cities in Europe".

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ACRONYMS

API Application Programming Interface

AWT Abstract Window Toolkit

CBD Central Business District

CPU Central Processing Unit

DOM Document Object Model

DPCM Development Proposal Choice Model

ELCM Employment Location Choice Model

GPL GNU Public License

GTFS General Transit Feed Specification

GUA Geographic Units of Analysis

GUI Graphical User Interface

HLCM Household Location Choice Model

HUDS Harvard Urban Development Simulation

JAXB Java Architecture for XML Binding

JEPP Java Embedded Python

JNI Java Native Interface

JVM Java Virtual Machine

LCC Land Cover Change Model

LUC Land Use Change Model

LT Land Use Transport

LTE Land Transport Ecology Model

LUTI Land Use Transport Interaction Model

MNL Multinomial Logit

OD Origin-Destination

OPUS Open Platform for Urban Simulation

OSM Open Street Map

PNI Python Native Interface

PSRC Puget Sound Region Council

PT Public Transport

PyXB Python W3C XML Schema Bindings

REDM Real Estate Development Model

ROI Return on investment

SAX Simple API for XML

SWT Standard Widget Toolkit

TLUMIP Transportation and Land Use Model Integration Project

UGM Urban Growth Model

UML Unified Modeling Language

W3C World Wide Web Consortium

XML Extensible Markup Language

XSD XML Schema Document

1 INTRODUCTION

Cities across Europe are facing challenges in urban growth. In the recent years there is a renewed interest in sustainable development and, thus, for the use of state-of-the-art land use and transport interaction (LUTI) models. Such models allow to perform comprehensive impact analysis and the evaluation of public policies such as congestion pricing or public transport. Forecasts about the impacts of policy measures can help voters, planners and elected officials to improve policy discussions. They provide a comprehensive tool to assist planners and decision makers in government assessing the impact of infrastructure measures (e.g., alternative combinations of transport, economic and environmental policies) and to improve policy and investment decisions in order to attain social, economic and environmental objectives in specific metropolitan areas.

LUTI models can be seen as simplifications of the urban system. They combine land use and transport models with feedback mechanisms between them. Their 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. Transport and land use are influencing each other in a dynamic and complex manner [Wegener, 2004; Strauch et al., 2005; Wegener, 2011; Geurs and Ritsema van Eck, 2001]: Accessibility provided by transport influences location decisions of developers, firms and households. Conversely, land use determines the need for spatial interaction.

Thus, an integrated view of the interactions between land use and transport is crucial to understand and forecast effects of modifications to the urban system [Borzacchiello et al., 2010; Wagner and Wegener, 2007], e.g., modifications on the structure of the transport system, the land use patterns and the environment.

Accessibility is a central measurement in this context. Generally, it is a measurement of attractiveness. The important aspect in the context of LUTI models is that accessibility measures how opportunities, e.g., workplaces, locations for shopping and leisure activities, are linked with each other via the transport network. Different accessibility components can be identified [Geurs and Ritsema van Eck, 2001; Geurs and van Wee, 2004]:

1. A land use component that deals with the number and spatial distribution of opportunities.
2. A transport component which describes the effort to travel from a given origin to a given destination.
3. A temporal component which considers the availability of activities at different times of day, e.g. in the morning peak hours.
4. An individual component that addresses the different needs and opportunities of different socio-economic groups, e.g., different income groups.

Accordingly, accessibility measurements can concentrate on one or several of these components [Geurs and Ritsema van Eck, 2001]:

- The infrastructure-based approach is based on the performance of the transport system.
- The activity-based measurement deals with the distribution of possible activity locations in space and time.
- A utility-based measurement of accessibility reflects the (economic) benefits, as the maximum expected utility, that someone gains from access to spatially distributed opportunities.

There are various accessibility measurements. One example is the so-called logsum that is used as a policy evaluation measure [de Jong et al., 2007]. It is an utility-based measurement of accessibility reflecting the (economic) benefits, as the maximum expected utility, that someone gains from access to spatially distributed opportunities [Geurs and Ritsema van Eck, 2001].

This dissertation is part of the SustainCity project [SustainCity Work Description, 2010], funded by the European Union Seventh Framework Programme (FP7). The project aims to address the need of forecasting the impacts of policy measures and, hence, the need for a framework that integrates modern micro-simulations of land use and travel models in a consistent way.

The present thesis focuses on the challenge to integrate the extensible, microscopic agent-based urban land use model UrbanSim with the agent-based transport simulation model MATSim ("Multi-Agent Transport Simulation"). To utilize the agent-based modeling technique, both models are directly linked at the person level. Another challenge is addressed by investigating in how far accessibility indicators can be pre-computed by the travel model in order to provide improved access and accessibility indicators as feedback from the travel model to enhance UrbanSim sub models reflecting the decisions of households, firms and developers.

The subsequent sections provide an overview about the SustainCity project and its goals. Also the major challenges of this thesis are described.

1.1 OVERVIEW OF THE JOINT RESEARCH PROJECT SUSTAINCITY

The SustainCity[1] [SustainCity Work Description, 2010; SustainCity www pages, accessed February 2012] project aims to improve urban simulation tools and to facilitate their application to help planners and decision makers in government assessing the impact of infrastructure measures and to improve policy and investment decisions [e.g. , Waddell, 2011a]. The project addresses both modeling and computational issues of coupling the latest micro-simulation models of land use and transport. The main challenges on the modeling side are to improve and add additional modules such as a demographic evolution module and environmental module.

The SustainCity project is realized by a consortium of European research institutions consisting of the Swiss Federal Institute of Technology (ETHZ) in Switzerland, the Ecole Normale Supérieure de Cachan (ENSC) in France, the Institut National d'Etudes Démographiques (INED) in France, the Université Catholique de Louvain (UCL) in Belgium, the Katholieke Universiteit Leuven (KLU) in Belgium, the STRATEC S.A. (a private company from Belgium), the National Technical University of Athens (NTUA) in Greece, the Berlin Institute of Technology (TU Berlin) in Germany, the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Switzerland, the Bocconi University

1 Project full title: Micro-simulation for the prospective of sustainable cities in Europe

(BU), the Université de Cergy Pontoise (UCP) in France and the University of California (UCB) in the USA.

More information about the project can be found on the project website at `sustaincity.org`.

1.2 OBJECTIVES

At this point, the general project objectives are summarized.

Three European cities, Zurich, Brussels and Paris, will be modeled in this project. The Open Platform for Urban Simulations (OPUS) [Miller et al., 2005; OPUS User Guide, 2011], an open source framework, will be used for this purpose. The main advantage of this shared platform is that it allows cumulative scientific contributions [Miller et al., 2005; OPUS User Guide, 2011; SustainCity Work Description, 2010], i.e., the platform offers the opportunity to add new modules or to improve and adapt existing modules. UrbanSim [Waddell, 2000, 2002; Waddell and Ulfarsson, 2004; Miller et al., 2005] is an integrated model system implemented within the OPUS platform that simulates interactions between land use, transportation, economy and the environment at large-scale metropolitan areas and over long time spans. UrbanSim is not a single model. It rather consists of several models reflecting decisions of individual households, firms, developers and the government and their interaction with the real estate market [Waddell, 2002]. UrbanSim was originally developed and applied for cities and metropolitan areas in the United States. Some of them are the urban regions of Honolulu (Hawaii), Eugene-Springfied (Oregon), Salt Lake City (Utah), Houston (Texas) and the Puget Sound region (state of Washington) [e.g. , Waddell and Borning, 2004]. In order to be consistent with particular characteristics of European cities, the OPUS/UrbanSim platform will be adapted to the European context and extended within this project as listed below. The European configuration of the UrbanSim modeling system is referred to as UrbanSimE. A comprehensive description about OPUS/UrbanSim is given in Sec. 2.6.

Such as other urban simulation models UrbanSim relies on the interaction with external transport models [Wegener, 2004]. Within the SustainCity project MATSim (Multi-Agent Transport Simulation) [Balmer et al., 2005a; Raney and Nagel, 2006; Balmer et al., 2009b], an agent-based travel model, and METROPOLIS [de Palma and Marchal, 2002], a dynamic transport model, will be integrated. The present dissertation will focus on MATSim. More in-depth information about MATSim is provided in Ch. 3 and at `matsim.org`.

The overall project objective includes developments in the following areas [SustainCity Work Description, 2010]:

1. The characteristics of European cities and their differences compared to American cities needs to be identified in order to build UrbanSimE. Cities in the United States and Europe, for example, differ in usage of public transport, the real estate market, the public and voluntary sector in the housing market as well as the road structure and the spatial configuration, in terms of shape and size, of parcels.

2. A collective decision module will be developed which takes individual interests as well as interests among different members of a household into account. This includes various dimensions such as residential location choice decisions of couples, spouses' employment choices and other long term decisions, such as car-ownership.

3. An external demographic evolution module will be provided that simulates annual changes in the composition of households, e.g., caused by immigration, emigration, births, deaths or the establishment of new households. Moreover, the existing job location model will be extended by a so-called firmographics module for modeling firm birth, death, growth and location choice decisions.

4. Environmental indicators will be added to capture amenities and negative externalities in the urban region such as pollution, noise and other environmental factors.

5. External travel models will be integrated to provide an alternative, improved accessibility feedback to UrbanSim. For this purpose MATSim, an agent-based travel model that is capable to simulate large real-world scenarios with several million agents, and METROPOLIS, a dynamic mesoscopic transport model, are selected.

6. The specification, estimation and validation of the integrated UrbanSim models will be improved to obtain a higher accuracy of predictions.

7. This new modeling platform UrbanSimE will be promoted among planners, decision makers in government and the academic community to support its application by European communities. This will be achieved by providing guidelines and required tools and organizing training courses and meetings for the above-mentioned audience.

As mentioned above, this dissertation focuses on item 5. In this work, MATSim will be integrated as a travel model plug-in into UrbanSim. The integrated framework is also referred to as MATSim4UrbanSim. In this configuration, MATSim performs a traffic flow simulation based on the land use and commuting patterns provided by UrbanSim. Furthermore, MATSim will be extended to perform high-resolution accessibility calculations to provide an alternative, improved accessibility feedback to UrbanSim. Various UrbanSim models make use of this feedback such as the household and employment location choice models, the developer model and the real estate price model.

The following summarizes the major challenges of the MATSim with UrbanSim integration [SustainCity Work Description, 2010], which are extensively discussed in Ch. 4 and 6. The main goals include:

- A robust software integration.
- The implementation of a travel demand generator that enables MATSim to take the urban structure and the synthetic UrbanSim population directly at the agent level as input in order to compute the traffic assignment.
- The introduction of accessibility computations, such as the standard logsum term, in MATSim to provide an alternative and improved accessibility feedback to UrbanSim.
- The computational efficiency of the traffic simulation is addressed by the so-called *warm* and *hot start* capability of MATSim that reduces computing times of simulation runs.

- The integrated modelling framework will be used for UrbanSim applications with different spatial resolutions (parcels and zones). This is another aspect that needs to be considered when linking MATSim with UrbanSim.

1.3 OVERVIEW OF THIS DISSERTATION

In Ch. 2 a literature review of current operational land use transport interaction (LUTI) models is provided. Strengths and weaknesses of LUTI models, their main evolution steps and their underlying subsystems are discussed. Three LUTI models, UrbanSim, ILUTE and ILUMASS, are presented. The next chapter introduces the agent-based micro-simulation travel model MATSim. Important key features and notations are explained. The MATSim architecture and process structure are presented in detail. Chapter 4 presents the interaction between MATSim with UrbanSim. In addition, the so-called *warm* and *hot start* capability of MATSim is described, which considerably reduces the computing times for the traffic simulation. Chapter 5 focuses on the application of the integrated modeling system and illustrates, through simulation runs of multiple scenarios, the impact of accessibility. In Ch. 6, the concept of accessibility and a new implementation of a high resolution accessibility computation approach in MATSim are explained. The proposed accessibility measurement is applied to a real-world scenario and the outcomes of various sensitivity tests are illustrated. This thesis concludes with a summary and outlook in Ch. 7. Software design issues and the implementation of the MATSim with UrbanSim integration is presented in Appendix A. In Appendix B, a sensitivity test is performed to investigate the impact from changes on the road network on the accessibility outcome (in addition to the accessibility illustrations in Ch. 5).

2 PRESENTATION OF URBANSIM AND OTHER LAND USE AND TRANSPORT INTERACTION MODELS

Land use and 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 [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 need an integrated view of the interactions between land use and transport [Wagner and 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. They help planners and decision makers assessing the impact of infrastructure measures and to improve policy and investment decisions [e.g. , Waddell, 2011a].

The aim of this chapter is to discuss strengths and weaknesses of such integrated models. In Sec. 2.1, general aspects of integrated models are discussed. Important evolution steps of land use and transport models are summarized and important underlying subsystems are identified and discussed in Sec. 2.2. Based on the reviews of [Wegener, 2004; Zöllig et al., 2011], an overview of existing LUTI models is provided in Sec. 2.3. A selection of disaggregated and agent-based models is discussed in greater detail. These are ILUTE (Sec. 2.4), ILUMASS (Sec. 2.5) and UrbanSim (Sec. 2.6). This chapter ends with a discussion and conclusion.

This chapter is an edited version of Nicolai, Zöllig Renner, and Nagel [2013].

2.1 A FRAMEWORK OF URBAN SYSTEMS

LUTI models can be defined as simplifications of the urban system. They allow to perform impact analysis and evaluation of plans and policies in respect of 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. To improve policy and planning decisions, such effects can then be evaluated. To provide a common communication base, the context of LUTI models is discussed, the modeled objects are specified, general modeling aspects are discussed and important notations are introduced. The following paragraphs relay on review literature of [Iacono et al., 2008; Hunt et al., 2005; Wegener, 2004; Verburg et al., 2004; Briassoulis, 2000].

The object being modeled with LUTI models is the urban system. According to Wegener [2004], it consists of nine subsystems as shown in Fig. 1. These are the urban environment, networks, goods transport, employment, workplaces, land use, housing, population and travel. They can roughly be grouped into a broader subsystem category. The environment, juristic regulations and infrastructures are the stage on which economic actors (persons) or actor groups (households, firms) perform their activities. The activities constitute the system of land use in the sense that it emerges from the decisions of the socio-economic actors where to perform an activity. The other subsystems are modified by some activities. Society constructs buildings and roads, changes land use regimes and influences ecosystems.

The activities can be seen as decision chains. Not all decisions are taken equally often. Decisions related to travel are taken rather spontaneously every day. In contrast, the decision to build a house is taken much less frequently. Even less frequent are group decisions which can even afford democratic decision processes. Hence, affected subsystems evolve with different speed. According to Wegener [2004], subsystems can be distinguished into:

- Very slow processes like building infrastructures or modifying a land use regime
- Slow processes like constructing buildings
- Fast processes like location choice decisions of households and firms
- Immediate processes like route choice decisions made on the road

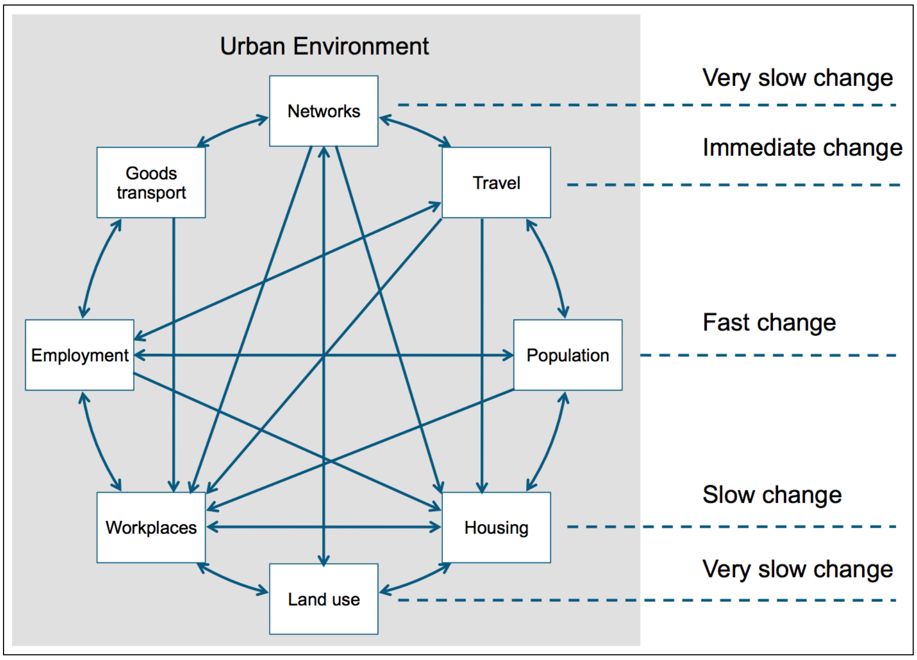


Figure 1: A model of urban models adapted from Wegener [1994].

The environment has a special position since it is an extremely complex subsystem in itself. It contains the anthropogenic elements which are interlinked by biological and physical processes. The anthropogenic urban system is embedded in the environment.

The activities with the inherent decisions determine the evolution of the urban system. The resulting processes are related with each other, e.g., the construction of a new residential building gives households new possibilities to reside. Not all processes are of the same kind, some are decision processes, some are physical processes, some are transition processes and others are political processes.

In Fig. 1 we can recognize two main parts of the anthropogenic urban system considered in LUTI models. The spatial distribution of activity places

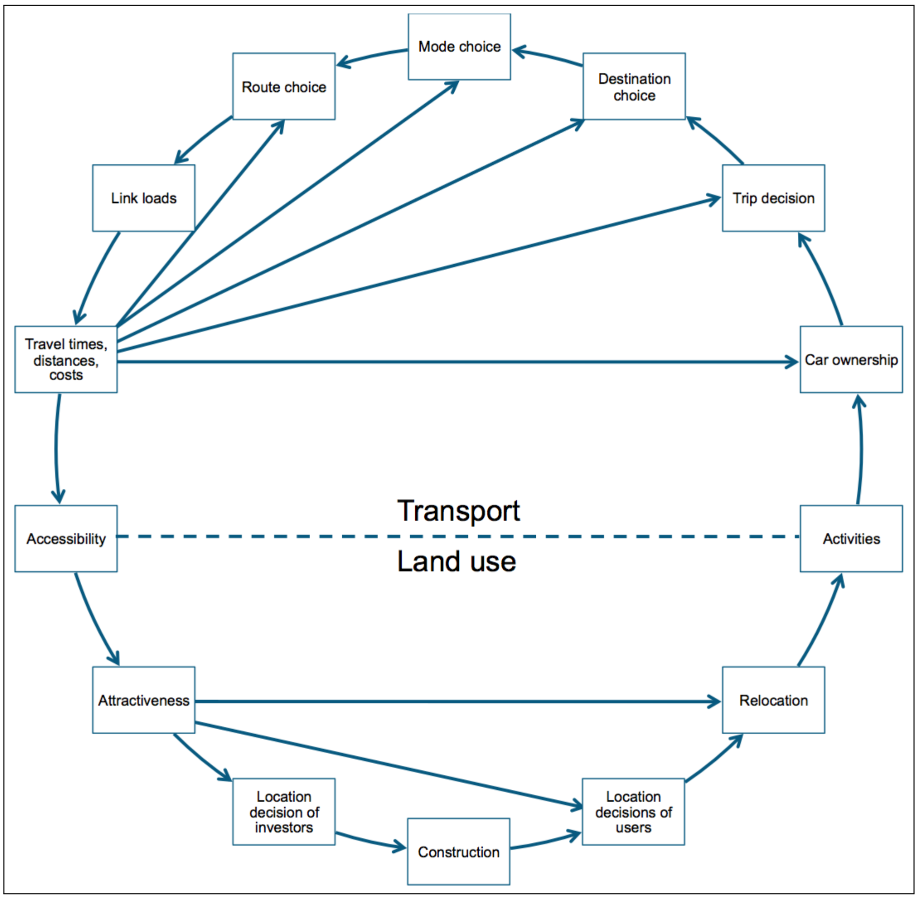


Figure 2: Feedback cycle between land use and transport systems adapted from Wegener [2004].

constitutes the land use system. This system consists of specialized places which facilitate certain activities like housing, working or traveling. Since specialization often leads to separation, traveling arises as an intermediate activity. From this point of view, the transport system is the subsystem of land use which connects 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 Fig. 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 infrastructures depends on capacity and usage, the attractiveness of locations is decreasing if it is more frequently visited.

Accessibility is a central measurement in this context, a comprehensive description is given in Ch. 6. Generally, it is a measurement of attractiveness of a location. It defines how well a given location can be reached, or how well other locations can be reached from this location. There are various definitions in a number of fields [Geurs and 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, e.g., workplaces, locations for shopping and leisure activities, are linked with each other via the transport network. The accessibility measurement used should thus be sensitive to variations in generalized travel costs and spatial distribution of facilities.

In modern societies, land use and transport are organized and designed according to the societies' needs. Society can decide where to locate which activities and how traveling and transport shall be organized. Society decides what infrastructures to build and approves land use plans. The societal decisions build the common background for the users to take their individual decisions.

2.2 MODELING THE URBAN SYSTEM

The term *model* is used quite extensively. Basically, a model denotes a simplification of reality [Gilbert and Troitzsch, 1999]. The researcher is the subject who perceives an object and creates a model of some form. The researcher uses different tools for modeling like his brain, but also language, pencils and computers. In analogy models can be found in different formulations such as ideas, concepts, theories, physical replications, mathematical formulas or computer programs. Usually, these terms are associated to different levels of detail in the formulation of a model.

The scope of LUTI models is given by the modeled subsystems and processes discussed before. They can be further distinguished into Land Use Transport (LT) and Land Transport Ecology (LTE) models, which have feedback cycle between the land use and transport component.

LUTI models can be denoted Land Use Change (LUC) models that try to explain for what purpose a piece of land is *used*. In contrast, Land Cover Change (LCC) models are only modeling categories of physical land nature. Urban Growth Models (UGM) are special cases of LCC models since they model the transition from unbuilt to built land.

Four different origins of general modeling techniques as the bases of existing LUTI models and three waves of development can be recognized [e.g. , Iacono et al., 2008; Timmermans, 2007]:

1. Spatial interaction and gravity models
2. Econometric models
3. Micro-simulation models

Each of the three waves has been triggered by theoretical and / or technological developments. The first LUTI model was implemented by Lowry [1964] on the basis of gravity theory. These first types of models, which have their roots in physics, have been overtaken by econometric models in the 1970s. The next step followed with the development of discrete choice modeling by McFadden [1981] and the development of information technologies, which made micro-simulation very attractive. The Harvard Urban Development Simulation (HUDS) was the first large scale model using micro-simulation [Wegener, 1995]. HUDS has been followed by other models like the Transportation and Land Use Model Integration Project (TULIP) which has been a further development of TRANUS. The third wave was triggered by the combination of theoretical developments in discrete choice modeling, technical feasibility of micro-simulation 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 environment to some extent. The feedback from the environment on the anthropogenic system is widely neglected.

A LUTI model is called *operational* if it is 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. A model is *operationalizable* if it is operational for at least one perimeter. The operationalization alone can be a labor-extensive project [Iacono and Levinson, 2008; Gru, 2000] as well as keeping it operational.

When modeling processes, dynamic models are needed. This means that not only a certain state of the urban system but also its development over time is simulated and, thus, the evolution of the system over time is mimicked. Gilbert and Troitzsch [1999] describe how this method works in general.

2.3 OVERVIEW OF LUTI MODELS

Currently, a number of LUTI frameworks exist in varying degrees of completeness and usability. This section provides (i) a general overview of operational LUTI models built on [Wegener, 2004; Zöllig et al., 2011] and (ii) focuses on three disaggregated and agent-based models by characterizing these models in greater detail. Considered models are: ILUTE, ILUMASS and UrbanSim which share some similarities such as the representation of land, floor space or housing market and the modeling of demographic changes. A detailed description of the selected models is provided in the subsequent sections.

At this point a list of operational LUTI models, based on [Wegener, 2004; Zöllig et al., 2011], is presented. The frameworks are listed in alphabetical order; more in-depth information on each model can be found in the given references:

1. BOYCE [Boyce and Zhang, 1997]
2. CUFM [Landis and Zhang, 1998a,b]
3. DELTA [Simmonds, 1999, 2001; Simmonds and Feldman, 2005; Bosredon et al., 2009]
4. ILUMASS [Wagner and Wegener, 2007; Beckmann et al., 2007; Strauch et al., 2005]
5. ILUTE [Salvini and Miller, 2005; Miller et al., 2004; Miller and Salvini, 2001]
6. IMREL [Anderstig and Mattsson, 1991]
7. IRPUD [Wegener, 1982a,b, 1986b,a, 1987, 1998b]
8. ITLUP [Putman, 1983, 1998]
9. KIM [Kim et al., 1989; Rho and Kim, 1989]
10. LILT [Mackett, 1991]
11. MEPLAN [Abraham and Hunt, 1999]
12. METROPILUS [Putman, 1996]
13. METROSCOPE [Metro Regional Government, 2013]

14. METROSIM [Anas, 1994, 1998]
15. MUSSA [Martinez, 1992b,a, 1997a,b, 2000]
16. NYMTC-LUM [Anas, 2002]
17. PECAS [Hunt and Abraham, 2003; Abraham and Hunt, 2007; Abraham et al., 2005]
18. POLIS [Caindec and Prastacos, 1995]
19. PUMA [Ettema et al., 2007]
20. RURBAN [Miyamoto et al., 1996]
21. STASA [Haag, 1990]
22. TIGRIS XL [Zondag, 2007]
23. TLUMIP [Weidner et al., 2007]
24. TRANUS [MODELISTICA, 2013]
25. TRESIS [Hensher and Ton, 2002]
26. UrbanSim [Waddell, 2000, 2002; Waddell and Ulfarsson, 2004; Miller et al., 2005; OPUS User Guide, 2011]

A tabular overview for three selected models is provided in Tab. 1. The notations are derived from [Wegener, 2004; Zöllig et al., 2011]. Some of them are introduced in Sec. 2.1 and 2.2. For a better readability, important notations are briefly described here.

MODELED PROCESSES This part indicates how many of the nine subsystems, explained in Sec. 2.1, are considered.

RESOLUTION All supported spatial units are listed and the temporal scale of one simulation period is given.

THEORETICAL FOUNDATION The theoretical foundation for the selected urban simulation models is based on discrete choice theory [Domencich and McFadden, 1975] which is used to model markets such as the job or land (or floorspace or housing) market or transport. In all three models, a *partial* equilibrium is calculated, i.e., equilibrium is computed separately for each sub-market. In *dynamic* models, independent model variables such as supply and demand, adjust to equilibrium with some delay. The models of land use, floorspace or housing markets of the selected models rely on *random utility maximization (RUM)*. The same concept is applied to localize activities.

FURTHER CRITERIA The selected models are simulating the evolution of the urban system over time by calculating a sequence of time or simulation steps. This classifies them as *recursive* models. The frameworks are *micro-simulation* models which are able to model disaggregated entities such as parcels or persons. In addition, ILUTE and ILUMASS include micro-simulation *transport models*. The *model structure* of each framework is classified as *composite*. This means that they consist of loosely coupled submodels where each submodel has its own independent internal structure

[Wegener, 2004]. 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]. All models are *calibrated* with *statistical* methods. Some of them are *operationalized* once, i.e., for one study region such as ILUTE and ILUMASS. In contrast, UrbanSim has been operationalisatized several times and *applied* to metropolitan areas or regions world wide. The term *operationalization* is explained in Sec. 2.2. Further, all models are under non-commercial license.

The following sections provide a comprehensive description for each selected model.

	Model	**ILUTE**	**ILUMASS**	**UrbanSim**
Modeled Processes	Comprehensiveness	8	9	5
	Network	yes	yes	exogenous
	Land use	yes	yes	yes
	Workplaces	yes	yes	yes
	Housing	yes	yes	yes
	Employment	yes	yes	yes
	Population	yes	yes	yes
	Goods transport	yes	yes	no
	Travel	yes	yes	exogenous
	Environment	no	yes	no
Resolution	Spatial resolution	grid cells, zones, parcels	grid cells	grid cells, zones, parcels
	Temporal resolution	flexible, depending on simulated subsystem	annual	annual
Theoretical Foundation	Equilibrium type	partial	none	partial
	Dynamics	dynamic	dynamic	dynamic
	Land use market	RUM	RUM	RUM
	Localization of activities	RUM	RUM	RUM
Further Criteria	Modeling technique	recursive	recursive	recursive
	Model structure	composite	composite	composite
	Transport model	micro-simulation	micro-simulation	none
	Aggregation	microscopic	microscopic	micoscopic
	Modeling concept	hybrid	hybrid	hybrid
	Calibration	statistical	statistical	statistical
	Operationalization	one application	one application	multiple applicationa
	Applied regions	Toronto (Canada)	Dortmund (Germany)	world wilde
	License	non commercial	non commercial	non commercial

Table 1: Characterization and comparison of selected LUTI models. This table is built on [Wegener, 2004; Zöllig et al., 2011]

2.4 ILUTE

ILUTE [Miller and Salvini, 2001; Miller et al., 2004; Salvini and Miller, 2005] (Integrated Land Use, Transportation and Environment) is an integrated, activity-based, micro-simulation urban modeling system developed by a consortium of Canadian researchers. It is based on the so-called "ideal" integrated urban model [Miller et al., 1998]. ILUTE is built as an experimental tool with the main research objective to investigate to which extent micro-simulation can be implemented within a practical model [Miller et al., 2004; Miller and Salvini, 2001]. A special feature of ILUTE is to track and capture 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. ILUTE has been applied for the greater Toronto and Hamilton area.

2.4.1 *Main components and key features*

Four contiguous main components are representing 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 micro-simulation model and simulates their activities and interaction. Objects in ILUTE include persons, transportation networks, the built environment, firms, the economy and the job market. The following summarizes design elements and key features of ILUTE as stated in [Salvini and Miller, 2005].

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 ex-spouse, 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 and 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 novel 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 [Salvini and Miller, 2005].

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.

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. On this account, 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.

Market demand and supply interactions are simulated in a disaggregate fashion by a disequilibrium based micro-simulation modeling framework for the built space markets [Farooq and 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.

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 and Miller, 2005; Side Effects www pages, accessed March 2013], a professional animation tool.

2.4.2 *TASHA*

The Travel Activity Scheduler for Household Agents (TASHA) represents the conceptual core of ILUTE [Miller and Roorda, 2003; Roorda et al., 2009]. It is a micro-simulation 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 and 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 suboptimal.
- "[...] 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 and 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.

Furthermore, TASHA has been extended for emission modeling to calculate and assess transport introduced air pollution [Hatzopoulou and Miller, 2010]. A recent effort integrates TASHA with MATSim to obtain a finer resolution for emission modeling [Hao et al., 2010]. A comprehensive description of MATSim is given in Ch. 3.

2.5 ILUMASS

The ILUMASS project (Integrated Land-Use Modeling and Transportation System Simulation) [Strauch et al., 2005; Beckmann et al., 2007; Wagner and Wegener, 2007] was under development between 2002 and 2006 by an interdisciplinary consortium of German research institutions. It made considerable progress in the state-of-the-art in integrated LTE models by incorporating three fully microscopic modules for urban land use, transport and the environment. ILUMASS has been applied for the urban region of Dortmund, Germany, including the city of Dortmund and 25 surrounding municipalities.

2.5.1 *Goals and features*

The main objective of the ILUMASS project was to develop a new type of integrated and microscopic land use, transport and environment (LTE) model that helps to explore feasible and successful policies and to achieve sustainable urban transport. It incorporates changes in land use, its impact on activity behavior and transport demand and the effects of transport and land use on the environment. A special feature of ILUMASS are two important feedback loops [Strauch et al., 2005]:

- The transport feedback to land use: Accessibility provided by the transport system influences location choice decisions of households, firms and developers.
- The environment feedback to land use: Environmental factors such as clean air or noise are included in location choice decisions of households and firms.

Another objective was to improve the micro-simulation of activity pattern and the resulting travel demand. To capture various attributes of activity scheduling decision processes, a survey with 402 individuals was carried out. This was realized with hand-held, computer aided self interviews of activity scheduling behavior with the dedicated Computerized Household Activity Scheduling Elicitor (CHASE) application [Strauch et al., 2005], which was developed by [Doherty and Miller, 2000].

It traces daily activity patterns, as for example, timing, location, involved persons and transport mode. A detailed description of the design and application of the ILUMASS scheduling process survey is given in [Rindsfüser et al., 2003]. The collected data serves as the empirical basis of the integrated micro-simulation framework for individual behavior.

In addition, ILUMASS takes account of shortcomings in previous LUTI models in terms of too aggregate temporal and spatial resolutions in order to model sustainable urban transport including [Strauch et al., 2005]: 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, the resulting impacts of traffic (e.g., nosie and air pollution) on the environment and the feedback from the environmental impacts on households and firms.

2.5.2 *Data*

The base year data incorporates synthetic "populations" of households, firms, 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.

- 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 license ownership and income.
- 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.

- 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.

The data is disaggregated into raster cells of $100m \times 100m$ size. The evolution from the base year data is simulated in annual steps.

2.5.3 *Main components*

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. A comprehensive description is given in [Strauch et al., 2005; Wagner and Wegener, 2007]. At this point, a brief overview is provided:

THE LAND USE MODULE 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, 1982a,b, 1994, 1998a, 2004]. Its macroscopic modules were re-implemented 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 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 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.

2.5.4 *Discussion*

The ILUMASS project ended in 2006. [Wagner and Wegener, 2007; Beckmann et al., 2007] discuss lessons learned:

1. Application programming interface (API): ILUMASS modules, developed by different research teams, are loosely coupled. The interfaces between the modules were well designed, but the coordination took a long time that was missing at the end of the project.

2. Testing: Even test runs were performed on the full study area. Also, according to the authors: "even if the error had been detected, the process of correcting it was not fast enough".

   A better approach would have been (i) to implement a testing process early during the API specification to test if the modules fit correctly, and (ii) to define small test scenarios that could run on any computer with the whole model chain to eliminate corresponding errors beforehand.

3. Data exchange: [Wagner and Wegener, 2007; Beckmann et al., 2007] state that a direct data exchange via the computer main memory would have been preferred because of the huge amounts of data. This would have required a more direct and collaborative software engineering, where ideally the software code would have been laid open within

the consortium. However, this was not an option. Instead, a file based approach was implemented that is more ponderous.

One solution would be to consider an open source structure in future projects.

4. Computing time: Some models of ILUMASS just took a few minutes, while others several weeks of computing time. The latter turned out to be too long to perform enough tests or scenarios.

   Wagner and Wegener [2007] state that one might consider multi-level models which could be microscopic where necessary and more aggregate where sufficient. However, the boundaries of "necessary" and "sufficient" are not clear.

5. Cooperation: Different disciplinary research traditions and standards made it time-consuming to cooperate among the project teams. Different attitudes and views had to be brought in line.

   [Wagner and Wegener, 2007; Beckmann et al., 2007] state that it would have been purposeful to solve these contradictions at an earlier stage of the project and, moreover, to explicitly schedule more time in the project to facilitate research teams to work together at one place.

2.6 URBANSIM

UrbanSim [Waddell, 2000, 2002; Waddell and 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 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, 2011a]. 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 the Paris/Île-de-France region.

2.6.1 *History*

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). The software is released as open source software under the GNU General Public License (GPL) [Miller et al., 2005].

2.6.2 *OPUS, UrbanSim, 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]. 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, 2011a; 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, 2011a].

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]. UrbanVision, a recent development project, extends UrbanSim by integrating highly interactive visualization capabilities. UrbanVision is a joint project between University of California Berkeley and Purdue University, founded by Metropolitan Transport Commission (MTC) and the National Science Foundation (NSF). The project objective is to integrate 3D geometry and a high resolution presentation into UrbanSim for use in urban planning, design and simulation [Waddell, 2011b]. It aims to bridge the gap between urban simulation and visualization [Vanegas et al., 2009] by generating plausible urban 3D models.

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.

In the following, no distinction between UrbanSim and OPUS is made for simplification.

2.6.3 *Data*

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) geographic, initial (ii) household and (iii) job information for a given base year. The geographic layer represents environmental, political and planning boundaries. Households are represented as individual objects (agents) including requisite attributes in order to model location choice decisions or travel behavior. Finally, the database includes job entries, incorporating the employment sector, representing employment [Waddell, 2002].

The primary source of the base year data usually comes from surveys or census. The UrbanSim models, described next, maintain the data store and simulate its evolution in annual steps [Waddell, 2002].

2.6.4 *Model structure*

As mentioned earlier, 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, firms, 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. The processing sequence of the main models are shown in Fig. 3. The bold arrows illustrate the sequence of events without necessarily indicating an interaction between contiguous models.

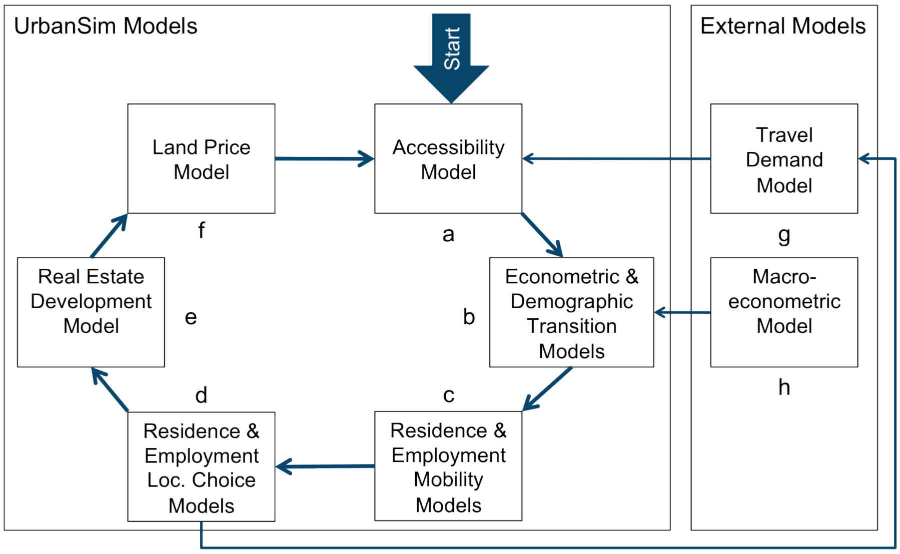


Figure 3: The sequence of UrbanSim main models after Waddell [2002].

Such as other land use transport interaction (LUTI) models, 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. A detailed description of the MATSim with UrbanSim integration is given in Ch. 4. Moreover, external macroeconomic models can be integrated.

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.

The scheduling and implementation of events (meaning read and write access to the database) of these individual model components is managed by a so-called coordinator model.

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 relocate. 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, its 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 has 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 multinomial 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 multinomial 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.

2.7 DISCUSSION AND CONCLUSION

The demand to forecast impacts of policy measures has emerged the need for simulation frameworks that integrate the micro-simulations of land use and travel models in a consistent way. Currently, several LUTI models exist that aim to address this task. This chapter presented three disaggregated and agent-based LUTI frameworks in greater detail which have been operationalized at least for one perimeter: ILUTE, ILUMASS and UrbanSim.

As stated earlier, e.g., in Sec. 1.2, two major objectives of the SustainCity project include to improve an existing LUTI model and to operationalize it for different European cities. The development of integrated land use and transport models is a long-term and relatively complex project that requires the collaboration of several research teams from different areas for many years [SustainCity Work Description, 2010; Zöllig et al., 2011]. Likewise, the operationalization for a specific study region alone can be a time and labor-expensive project [Iacono and Levinson, 2008; Gru, 2000] as well as keeping it operational. Taking these considerations into account, the UrbanSim modeling framework was selected for this project.

UrbanSim is an flexible open source framework which has been widely operationalized. Some examples of UrbanSim case studies include the urban regions of Honolulu (Hawaii), Eugene-Springfied (Oregon), Salt Lake City (Utah), Houston (Texas) and the Puget Sound region (state of Washington) [e.g., Waddell and Borning, 2004]. Its main advantage is that it provides a shared modeling platform which allows cumulative scientific contributions. In other words, it offers the opportunity to improve existing models and to customize and adjust them to a specific region. New models can be developed and integrated. Another advantage is the usability provided by the graphical use interface (GUI) that allows to create and configure models in detail.

3 PRESENTATION OF THE MATSIM FRAMEWORK

As discussed in the previous chapter, the UrbanSim framework, an urban simulation model, will be used in this thesis. Such as other urban simulation models like DELTA, CUFM, MUSSA, POLIS or RURBAN, UrbanSim does not model transport itself [Wegener, 2004]. Instead, it relies on the interaction with external transport models to update traffic conditions.

For this purpose, the MATSim ("Multi-Agent Transport Simulation") traffic simulation framework will be used. MATSim [Balmer et al., 2005a; Raney and Nagel, 2006; Balmer et al., 2009b] is a disaggregated agent-based transport model that is designed to simulate several million travelers (agents) individually for large real-world transport scenarios. Moreover, it provides additional advantages; some of them are simulating time-dependent congestion and time-dependent mode choice. Computation times can be accelerated by running small samples of a scenario. MATSim has been applied to large scale scenarios in Zurich, Berlin and many other cities [Balmer, 2007]. The framework is currently a joint effort by groups of Prof. Nagel (TU Berlin), Prof. Axhausen (ETH Zürich) and Senozon, a commercial company in Switzerland, founded by former PhD students.

This chapter presents the MATSim simulation framework. The following section provides an overview about the key features of MATSim. In Sec. 3.2, a brief overview about the general MATSim simulation process structure is given. Agent plans and MATSim layers are discussed in Sec. 3.3 and 3.4. In MATSim, the demand of each individual agent is improved in the iterative demand optimization process. This process is explained in Sec. 3.5. The underlying scoring function is described in Sec. 3.6. This chapter ends with referring to the MATSim post-process analysis.

This chapter is an edited version of Nicolai and Nagel [2013].

3.1 FEATURES

Important key features of MATSim include:

- MATSim is distributed under the GNU Public License (GPL) and can be used free of charge.
- The modular approach allows to replace or add functionality to MATSim to model agent behavior.
- MATSim provides a detailed output from the traffic simulation for further analysis which can be visualized either with "via", a commercial tool from Senozon, or OTFVis, an open source package for MATSim. Both tools visualize the simulated traffic and show inter alia the location and route of each agent, where Senozon "via" provides additional analysis tasks.
- MATSim also provides a time dependent network. It allows to perform changes in the network at any time of day. Several link attributes such as the flow capacity, free flow speed and number of lanes of any link can be adapted. This allows to apply different scenarios, e.g., for policy measures or evacuation scenarios.

- MATSim is capable to simulate different toll schemes such as distance, cordon or area toll, which are discussed in [Kickhöfer et al., 2010; Nagel et al., 2008; Rieser et al., 2008; Grether et al., 2008; Beuck et al., 2006]. They can be limited upon a part of the network and, as mentioned above, triggered at specified times (time-dependent), i.e., the amount agents have to pay for the toll can differ during the simulated day. This feature is also available in the MATSim with UrbanSim integration called MATSim4UrbanSim. The integration is described in Sec. 4.1.

- MATSim provides several ways to simulate public transport (PT):

  – **Transit Schedule**: The public transport service can be modeled in high detail by using the MATSim public transit schedule [Rieser and Nagel, 2009; Rieser, 2010]. It includes information about public transit lines, their routes, the travel time between stops and the time of departure at the start of the route. In a recent effort, General Transit Feed Specifications (GTFS) [General Transit Feed Specification www pages, 2012] can be converted into MATSim transit schedules [Ordonez and Erath, 2011], see also `http://matsim.org/docs/extensions/gtfs2transitschedule`. GTFS is a format for public transportation schedules that can be used by public transport agencies to publish their transit data and by developers to implement applications that are built on this format [General Transit Feed Specification www pages, 2012].

  – **Pseudo PT**: A simple model, called "pseudo pt", is capable to handle non-car modes. It estimates travel times by public transport by making the following assumptions [Grether et al., 2009; Rieser and Nagel, 2009]: It is assumed that the travel distance between activity locations is composed of the beeline distance multiplied with a beeline distance factor, which is by default 1.3. The pt speed (km/h) is configurable. The resulting travel times are determined by:

$$\frac{BeelineDistance * BeelineDistanceFactor}{PtSpeed} \tag{1}$$

  This approach models public transport continuously and without capacity constraints [Grether et al., 2009; Rieser and Nagel, 2009]. It works without any knowledge about the public transport service in an area. The estimated travel times are used to create "teleported" public transport legs; a leg describes a part of a trip that uses exactly one transport mode [Balmer et al., 2005a]. In other words, agents that are using these public transport legs are teleported from their current location to the destination location.

  – **Improved Pseudo PT**: Within this dissertation, two additional approaches were implemented to integrate public transport (PT) that get in line between the public transit schedule and the pseudo pt approach:

    * Given an input table with public transit stops and the associated coordinates, a matrix is generated including travel times and travel distances for any pair of stops. Travel times are

determined based on Eq. 1 with a fixed pt speed of 25km/h. Travel distances are given by the numerator of Eq. 1, i.e., beeline distance between two stops multiplied by the beeline distance factor.

* Another approach extracts a stop-to-stop impedance matrix from an existing VISUM [PTV AG, 2009a,b] model. That matrix contains travel times and distances between two stops provided by the VISUM model.

In both cases, traveling by public transport is executed as teleportation in MATSim, i.e., simulation of public transport is not performed on the physical road network. The overall public transport travel times and distances are then determined as follows:

* The nearest ptStop to the coordinates of the current activity (origin) is determined.
* The nearest ptStop to the coordinates of the next activity (destination) is determined.
* The according travel time or distance is queried from the matrix.

The total travel time is composed of:

$$TT_{pt,ik} = tt_{wlk,gap,i} + tt_{pt,matrix} + tt_{wlk,gap,k}\ , \tag{2}$$

where TT_{pt} is the total travel time to get from activity location i to k, $tt_{wlk,gap,i}$ and $tt_{wlk,gap,k}$ are the travel times on foot, with a fixed walking speed of 5km/h, to overcome the gap between the activity locations i and k respectively to their nearest pt stop based on the beeline distance. Finally, $tt_{pt,matrix}$ is the travel time between the two stops, given by the matrix.

The total travel distances are determined analogously:

$$TD_{pt,ik} = td_{gap,i} + td_{pt,matrix} + td_{gap,k} \tag{3}$$

Here, $TD_{pt,ik}$ is the total travel distance, $td_{gap,i}$ and $td_{gap,k}$ are the beeline distances between location i and k respectively to their nearest pt stop, $td_{pt,matrix}$ is the travel distance between the two stops from the matrix.

3.2 MATSIM PROCESS STRUCTURE

At this point, a brief overview about the general MATSim simulation process structure is provided as described in [Balmer et al., 2009b]. It consists of the following parts:

- **Initial demand**: MATSim requires the physical infrastructure, determined by the road network and facilities (i.e., activity locations like home, work, shopping or leisure) and the population including the demand of each individual person. The initial demand for each agent is usually generated based on micro census and/or survey data.
- **Iterative demand optimization**: In an iterative demand optimization process, the demand for each individual agent is improved. It takes into account physical constraints, e.g., the road network, and the interaction between the agents. The optimization process consists of an

iteration cycle with three main steps, “Execution”, “Scoring” and “Re-planning”, which are explained below in more detail.

- **Analysis**: Finally, the simulation results such as the resulting population and demand and the traffic conditions on the network can be used for post-process analysis.

These parts will be described in more detail in the subsequent sections.

3.3 AGENTS AND PLANS

Each person or traveler in MATSim is modeled as an individual agent. The demand of an agent is called plan [Balmer et al., 2009b]. A plan encodes the daily routine of an agent. It contains the agent’s travel schedule including its intended activities and routing decisions between the activity locations [Balmer et al., 2005a]. Moreover, a plan captures (i) the order, type, location, duration as well as other time constraints for every activity and (ii) the selected mode, route and expected departure and travel times of each leg [Balmer et al., 2005a]. A leg describes a part of a trip that uses exactly one transport mode [Balmer et al., 2005a]. An example plan is illustrated and explained in Fig. 4.

```
<person id="12345" employed="yes">

    <plan score="123.5" selected="yes">

        <act type="home" link="1000" x="100.0" y="100.0" end_time="07:30:00" />

        <leg mode="car" dep_time="07:30:00" trav_time="00:20:00" arr_time="07:50:00">
            <route type="links"> 1000 1001 1002 1003 </route>
        </leg>

        <act type="work" link="1003" x="200.0" y="200.0" start_time="07:50:00" max_dur="08:00:00" end_time="15:50:00" />

        <leg mode="car" dep_time="15:50:00" trav_time="00:20:00" arr_time="16:10:00">
            <route type="links">1003 1004 1005 1000</route>
        </leg>

        <act type="home" link="1000" x="100.0" y="100.0" start_time="16:10:00" />
    </plan>

</person>
```

Figure 4: This illustrates the demand or plan of a fictitious MATSim agent. The agent with the id 12345 intends to leave home (located at link 1’000) to go to work. The selected route consists of four links. The expected travel time by car takes 20 minutes. After 8 hours staying at work the agent travels back home, which takes 20 minutes travel time by car. This plan describes the complete daily routine of agent 12345.

3.4 MATSIM LAYERS

The MATSim framework considers two layers [Raney, 2005; Balmer et al., 2005a; Nagel and Marchal, 2007; Raney and Nagel, 2006], (i) a “physical” and (ii) a “strategic” or “mental” layer:

The (i) physical layer, in the following called mobility or traffic flow simulation, represents all physical aspects of the environment. It expresses what agents can do in this environment and how they interact with each other, e.g., agents get stuck in congestion. This layer includes the road network infrastructure, agent activities, their interaction among each other as well as the resulting network load.

The (ii) strategy layer enables agents to make decisions and to adapt or optimize their plans based on what they experienced in the physical layer. It includes the scheduling of activities, locations and transport modes as well as behavioral parameters.

3.5 ITERATIVE DEMAND OPTIMIZATION PROCESS

As stated before, the simulation takes the representation of the infrastructure and the population including their daily plans as input [Balmer et al., 2009b]. In [Balmer et al., 2005a; Raney and Nagel, 2006; Balmer et al., 2009b] the simulation process is explained in detail. It consists of an iterative loop with three steps, see Fig. 5. The main steps are summarized in the following:

- **Execution**: The mobility simulation executes all agents with their selected plan simultaneously on the road network (physical layer). At this stage, agents are interacting with the physical environment and with other agents.

  The mobility simulation is implemented as a queue simulation. In this approach links or road segments are represented as first-in first-out (FIFO) queues following three simple rules [Gawron, 1998; Cetin et al., 2003; Balmer et al., 2005a]: (i) Agents are dwelling for a certain time on a link; the minimum dwelling time is given by free speed travel times. (ii) Agents or vehicles cannot enter a link whose storage capacity has been reached. (iii) The number of vehicles leaving a link is determined by the flow capacity.

- **Scoring**: All executed plans are scored by a utility function that determines the performance of each plan. For this task, various scoring functions can be used. By default, MATSim uses the so-called Charypar-Nagel scoring function [Charypar and Nagel, 2005], which is presented next in Sec. 3.6.

- **Re-planning**: In this step, mentioned above as the strategy layer, some agents choose between existing plans, some re-evaluate plans with bad scores and some obtain new plans by modifying existing ones depending on the selected strategies and their probabilities. In MATSim, this is implemented via so-called re-planning modules capturing one or more travel behavior attributes. Some of them are:
  - Plan choice module: This module enables agents to select between existing plans. Agents usually choose the plan with the highest score [Balmer et al., 2005a].
  - Time allocation module: This module changes the durations and/or shifts the departure times of activities [Balmer et al., 2005a].
  - Router module: All routes of an agent's plan are recomputed by using the updated generalized costs for each link from the last traffic flow iteration. The router is a time-dependent best path algorithm [Lefebvre and Balmer, 2007], where best path is defined as the one with the least negative utility [Balmer et al., 2009b].
  - Mode choice module: Originally, there was no dedicated mode choice module. Instead, it had to be ensured that each agent has at least one car and one non-car (e.g., public transit) plan [Grether et al., 2009; Rieser and Nagel, 2009]. An implementation of this module allows agents to switch between available transport modes for single trips within their plans.

  These modules take their decisions based on the outcome of the traffic flow simulation, e.g., taking congestion effects into account [Balmer et al., 2005a]. The number of modules are not limited to those mentioned above. More than one module can be used at the same time.

Every module is assigned a weight that determines the probability if a module is applied to an agent.

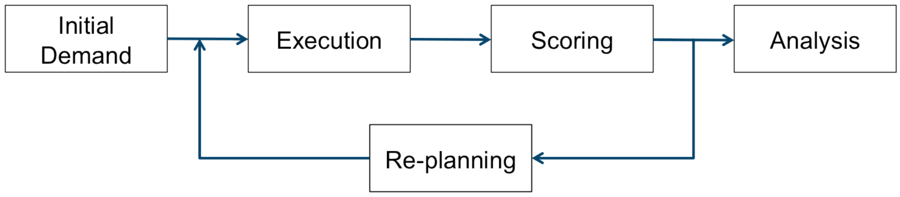


Figure 5: This shows the process structure of MATSim. Once the initial demand is generated, agent's plans are optimized in an iterative process until a relaxed state of the system (usually a user equilibrium) has been reached. Finally, MATSim obtains detailed output from the traffic simulation, which can be used for further analysis.

In order to achieve consistency between the physical and strategic layer, a feedback between both layers is introduced into the simulation structure [Kaufman et al., 1991; Bottom, 2000]. This is done by running the mobility simulation with agents' selected plans, using the re-planning modules to update the plans based on the output of the mobility simulation, then execute these in the mobility simulation again, etc. [Balmer et al., 2005a].

The repetition of the iteration cycle coupled with the agent memory, the capability to remember more than one plan per agent, enables agents to improve their plans over several iterations [Balmer et al., 2005a].

The iteration cycle continues until a *relaxed* state of the system has been reached. In [Balmer et al., 2009b, p.70] it states that a relaxed state is reached when "the utility for each agent does not noticeably change through variation of the day plans" and "the trajectory of average utility per iteration represents a stationary process" – the underlying scoring function. There is no quantitative measure of when this state is reached; usually, the iteration cycle is repeated until the outcome is stable [Balmer et al., 2005a].

3.6 EVALUATION OF THE PERFORMANCE OF A PLAN WITH THE SCORING FUNCTION

The MATSim scoring function is described in [Charypar and Nagel, 2005]. At this point the updated notation from [Kickhöfer et al., 2011] is used.

The utility of an executed plans is computed as:

$$V_p = \sum_{i=1}^{n} \left(V_{perf,i} + V_{late,i} + V_{tr,i} \right) , \tag{4}$$

with V_p as the accumulated utility for a given plan p with n activities, $V_{perf,i}$ is the utility for performing activity i, $V_{late,i}$ is the disutility, i.e. a negative utility, of being late at activity i, and $V_{tr,i}$ is the disutility of traveling from activity i to activity $i+1$. Plans are assumed to wrap around a 24-hr day, for that reason, the last activity is assumed to be the same as the first, and in consequence there are as many trips as there are activities.

The positive utility for performing an activity has a logarithmic form, it is defined as:

$$V_{perf,i}(t_{perf,i}) = \beta_{perf} \cdot t_{*,i} \cdot \ln\left(\frac{t_{perf,i}}{t_{0,i}}\right) \tag{5}$$

Here, t_{perf} is the actually performed duration of activity i, t_* is the typical duration of activity i, β_{perf} gives the marginal utility of any activity at its typical duration. $t_{0,i}$ is related to the minimum duration and to the importance of an activity, but has no effect as long as activity dropping is not part of the simulation.

The disutility for being late is defined as:

$$V_{late,i}(t_{late,i}) = \beta_{late} \cdot t_{late,i}, \tag{6}$$

where β_{late} is the marginal utility for being late ($utils/h$), while $t_{late,i}$ gives the amount of time (in h) of being late at activity i.

Originally, the disutility of traveling in [Charypar and Nagel, 2005] is given as:

$$V_{tr,i} = \beta_{tr} \cdot t_i, \tag{7}$$

where β_{tr} is the marginal utility of traveling, given in $utils/h$, converting travel times into utils and t_i is the travel time (in h) to travel to activity i.

An extended version of the disutility of traveling is based on [Moyo O. and Nagel, 2012]:

$$V_{tr,i} = \beta_{tr} \cdot t_i + \beta_{td} \cdot td_i + \beta_{ls} \cdot ls_i, \tag{8}$$

Again, β_{tr} is the marginal utility of traveling, and t_i is the time traveling to activity i. β_{td} gives the marginal utility of distance given in $utils/meter$ (typically set to zero), β_{ls} is the utility of changing vehicles in public transit, also called utility of line switch, td_i is the travel distance (in $meter$), and ls_i is the number of vehicle changes. The typical version of $V_{tr,i}$, however, does not include vehicle changes, but toll if road pricing is used:

$$V_{tr,i} = \beta_{tr} \cdot t_i + \beta_{td} \cdot td_i + \beta_m \cdot m_i, \tag{9}$$

with β_m as the marginal utility of money ($utils/monetary\ units$) and m_i as the monetary toll costs.

3.7 ANALYSIS

At the end of a run MATSim obtains a congested road network. This can be used for further analysis, e.g., to compute access and accessibility indicators as feedback for UrbanSim as part of the MATSim with UrbanSim integration described in Ch. 4.

4 COUPLING MATSIM WITH URBANSIM

In the previous chapters, the micro-simulation models UrbanSim and MATSim were presented. This chapter summarizes the steps integrating UrbanSim with MATSim directly at a microscopic person centric level in Sec. 4.1. This integration is also referred to as MATSim4UrbanSim. Section 4.1.2 provides a brief overview about the data requirements for MATSim and UrbanSim. The following section (Sec. 4.1.3.2) looks at the feedback indicators for UrbanSim that will be provided by MATSim. A major challenge includes that traffic models typically require large amounts of computing time. This will be addressed by a so-called *warm* and *hot* start capability of MATSim, which are both described in detail Sec. 4.2. Methods, concepts and software design decisions to couple MATSim with UrbanSim are presented in Appendix A.

4.1 INTEGRATION APPROACH

This section explains the coupling of MATSim with UrbanSim, presents the data requirements for both simulation models and looks at the MATSim feedback that will be used as input for various UrbanSim models.

This section can be found in similar form in Nicolai and Nagel [2011, 2012a, 2013]; Nicolai [2012].

4.1.1 *MATSim4UrbanSim at a glance*

As discussed earlier, (Sec. 2.6) UrbanSim is an extensible urban simulation model that aims at simulating interactions between land use, transportation, the economy and the environment [e.g., Waddell, 2002]. It mainly consists of six models reflecting the decisions of households, firms, developers and governments [Waddell, 2002]; for more information see Sec. 2.6.4.

The input to the UrbanSim models includes the base year data, the access indicators from the external travel model and control totals derived from external macro-economic forecast models, see also Fig. 3 in Sec. 2.6.4. The base year data store contains the initial state of a scenario. The database includes geographic information, initial household and job information, etc., for a given base year. The primary source of the base year data usually comes from surveys or the census. The UrbanSim models reflecting the decisions of households, firms, developers and governments (as policy inputs) maintain the data store and simulate its evolution from one year to the next [Waddell, 2002].

The interaction between MATSim and UrbanSim is a bi-directional relationship as depicted in Fig. 6 and consists of three main steps:

1. When UrbanSim iterates in annual steps, it calls MATSim from time to time, at most once per annual step, and passes the traffic network together with location and socio-economic characteristic of individual residents and firms as input including attributes such as the person ID as well as the residence and job location of each individual person in UrbanSim.

2. Given the input tables from UrbanSim, MATSim generates the traffic assignment. An overview about the general MATSim simulation process structure is provided in Sec. 3.2. Finally, it returns the resulting access and accessibility indicators. Then MATSim terminates.

3. Once MATSim has terminated, UrbanSim takes back control. It reads the indicators and updates the data store for the next UrbanSim iteration. UrbanSim models that make use of the updated traffic conditions are the Household and Employment Location Choice Models as well as the Real Estate Price Model; as already discussed in Sec. 2.6.4.

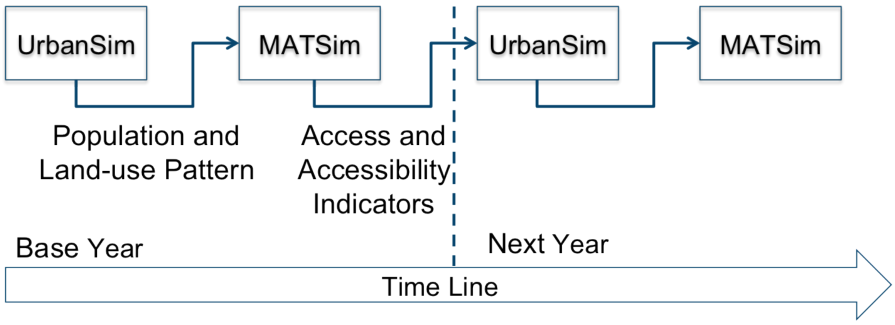


Figure 6: This shows the interaction sequence between UrbanSim and MATSim. UrbanSim calls MATSim in regular intervals and passes the current population and land use pattern. MATSim computes the traffic based on the provided information and the resulting access and accessibility indicators. UrbanSim uses these indicators for the next year (= iteration) as input for various models.

In step 1, UrbanSim provides three input tables for MATSim, which are described in Sec. 4.1.3.1 in more detail: For UrbanSim parcel models these are the persons, jobs and parcels table; for zone models the parcels table is replaced by a zones table. The tables are structured as follows. Each person of the persons table refers to a parcel or zone of the residence location. Working persons also refer to jobs which refer to a parcel or zone of the working place. Parcels or zones possess coordinates. Based on this information, home-work-home commuting trips are constructed in MATSim. Route and departure time assignment are done inside MATSim. More complex, e.g., activity-based, demand patterns are possible with MATSim, but are not implemented in the present version of MATSim4UrbanSim.

The next section explains the UrbanSim and MATSim data requirements.

4.1.2 *Data requirements*

This section provides a brief overview about the data requirements for MATSim and UrbanSim. This text can be found in similar form in [Nicolai, 2012].

UrbanSim is a very flexible tool. One consequence of this flexibility is that many variable names in data sets are not standardized. For example, an x-coordinate could be named "x_coord_sp" in one model and "xcoord" in another. The reason why this works internally is that for every UrbanSim application the models, e.g., household location choice model, are specific to the application and thus refer to the specific variable names that are in use for that specific application.

Within the SustainCity project, two European metropolitan areas, Zurich and Brussels, will be modeled based on the integrated MATSim for UrbanSim modeling framework, see Sec. 1.1 and 1.2. In terms of the travel model plug-in this means that it must to react to specifics of the given case studies. In the following, these specifics are referred to as "Zurich parcel" or "Brussels zone" implementation.

4.1.2.1 *UrbanSim data requirements*

In order to create the input tables for MATSim, UrbanSim requires certain data sets and attributes to reflect where a person lives and works. A compilation of these data sets and attributes is given below for the parcel and zone version of UrbanSim. Technically, persons are linked to residences and work places and these in turn are linked with a spatial reference or coordinate via unique identifiers (IDs) as illustrated in Fig. 7 and Fig. 8 for the UrbanSim parcel and zone version.

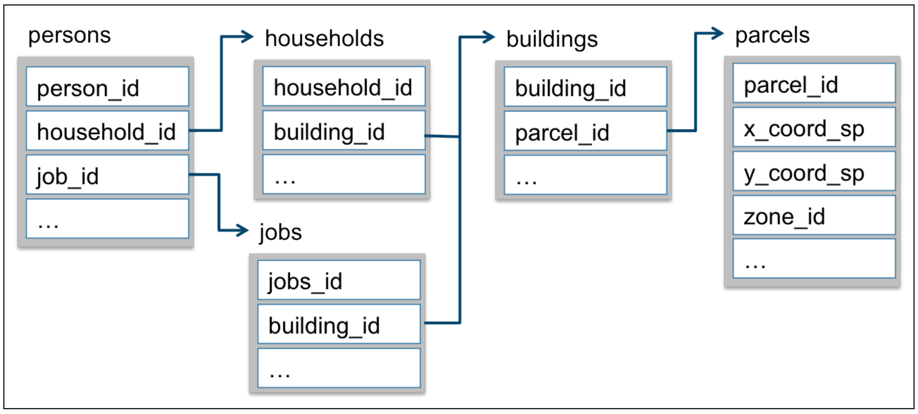


Figure 7: This illustrates the required data sets (boxes) and attributes (white boxes) for UrbanSim parcel models. The blue arrows indicate how these data sets are linked with each other via attribute names.

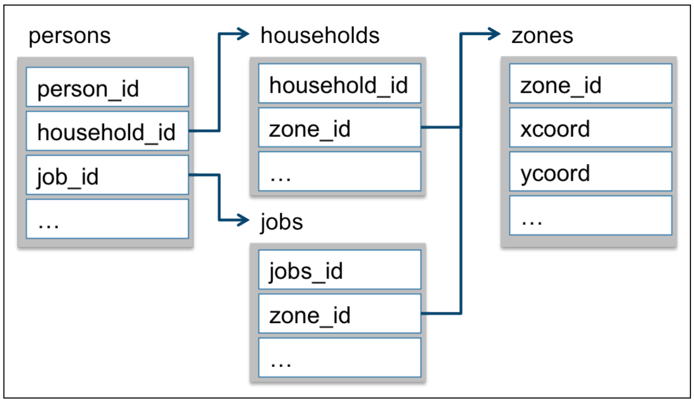


Figure 8: This illustrates the required data sets (boxes) and attributes (white boxes) for UrbanSim zone models. The blue arrows indicate how these data sets are linked with each other via attribute names.

urbansim parcel models For UrbanSim parcel models such as the Zurich application the following data sets and attributes in parentheses are required:

- persons (person_id, household_id, job_id)
- households (household_id, building_id)
- jobs (job_id, building_id)
- buildings (building_id, parcel_id)
- parcels (parcel_id, x_coord_sp, y_coord_sp, zone_id)
- zones (zone_id)

URBANSIM ZONE MODELS For UrbanSim zone models, e.g., the Brussels application, the following data sets and attributes in parentheses are required:

- persons (person_id, household_id, job_id)
- households (household_id, zone_id)
- jobs (job_id, zone_id)
- zones (zone_id, xcoord, ycoord)

4.1.2.2 *MATSim data requirements*

The mandatory input for MATSim is a configuration file, a network file and the land use and population pattern of the current UrbanSim simulation year that are briefly introduced in the following.

CONFIGURATION The configuration file provides resources like the location of the network file and parameter settings that are adjusting the behavior of MATSim. These settings are done in the UrbanSim graphical user interface (GUI). For more information on this, please refer to Appendix A. Given these settings, UrbanSim automatically generates a configuration file and passes it as an argument to MATSim at each execution.

NETWORK The network represents the transport infrastructure. MATSim network files contain links and nodes each with its specific attributes such as the node coordinate and a description of a link. Links are defined by a start and an end node (from="<node-id>" and to="<node-id>"). Further, important link attributes are the length, capacity (vehicles per hour), free-flow speed in meters per second (free speed) and number of lanes (permlanes). Recently, an additional attribute was added specifying by which transport mode (modes) the link can be used. An example network file is given in Lst. 1. The MATSim network is stored in XML format, where XML is an acronym for Extensible Markup Language [XML www page, accessed 2013].

LAND USE AND POPULATION PATTERN As mentioned in Section 4.1.1, the current land use and population pattern are provided to MATSim as input by several data set tables. Such tables are including the residence and job location of each individual person in UrbanSim. Based on this information, MATSim generates the traffic assignment as described in Section 3.2.

Listing 1: An example for a MATSim network file.

```
<?xml version="1.0" encoding="UTF-8"?>
<!DOCTYPE network SYSTEM "http://www.matsim.org/files/dtd/network_v1.dtd
    ">

<network name="example">
    <nodes>
        <node id="0" x="505046.8125" y="137967.7969" />
        <node id="1" x="520580.9063" y="147882.7969" />
        <node id="2" x="594615.5" y="199259.2969" />
        ...
    </nodes>

    <links capperiod="01:00:00" effectivecellsize="7.5"
        effectivelanewidth="3.75">
        <link id="0" from="0" to="1" length="6243.0" freespeed
            ="27.77777777777778" capacity="4000.0" permlanes="2.0"
            oneway="1" modes="car" />
        <link id="1" from="1" to="0" length="6243.0" freespeed
            ="27.77777777777778" capacity="4000.0" permlanes="2.0"
            oneway="1" modes="car" />
        <link id="2" from="1" to="2" length="949.0" freespeed
            ="33.333333333333336" capacity="4000.0" permlanes="2.0"
            oneway="1" modes="car" />
        ...
    </links>
</network>
```

4.1.3 *Output*

4.1.3.1 *UrbanSim output*

At this point, the UrbanSim output for MATSim is described. UrbanSim passes the following tables including the required data sets and attributes listed in Sec. 4.1.2.1. Tables are written in tabulator-separated format.

URBANSIM PARCEL MODELS The UrbanSim output for parcel models consists of the following tables, see also Table 2:

- **Person Table**: This file includes a person ID and the corresponding home and work parcel ID for each individual UrbanSim person, where the parcel IDs are referring to the parcel table described below.
- **Job Table**: This gives the job-, parcel- and zone ID for each job in UrbanSim. The parcel ID refers to the parcel table (next item).
- **Parcel Table**: This table consists of a parcel ID, the parcel centroid given as x, y coordinates and the zone ID in which the parcel is located. Given this information, home and work locations can be located geographically.
- **Zone Table**: This table stores the zone id and the x and y coordinates of the zone centroid for each UrbanSim zone. Centroid coordinates are either given or can be determined in MATSim by averaging over all parcel coordinates of an associated zone.

URBANSIM ZONE MODELS In case of UrbanSim zone models, the following three tables are written; see also Table 3:

- **Person Table**: This file includes the person ID as well as the zone ID of the home- and work location of each individual UrbanSim person. The zone IDs are referencing the zone table described below (last item).
- **Job Table**: This gives the job and zone ID for each available job in UrbanSim, where the zone ID refers to the zone table (next item).
- **Zone Table**: As described for UrbanSim parcel models this table stores the zone ID and the x and y coordinates of the zone centroid. At this point, centroid coordinates are given by UrbanSim.

UrbanSim Parcel Output		
Table	**Indicators**	**Data Type**
Person data set table	person_id	long
	parcel_id_home	long
	parcel_id_work	long
Job data set table	job_id	long
	parcel_id_work	long
	zone_id_work	long
Parcel data set table	parcel_id	long
	x_coord_sp	double
	y_coord_sp	double
	zone_id	long

Table 2: Constructed output tables from an UrbanSim parcel appliction for MATSim.

UrbanSim Zone Output		
Table	**Indicators**	**Data Type**
Person data set table	person_id	long
	zone_id_home	long
	zone_id_work	long
Job data set table	job_id	long
	zone_id_work	long
Zone data set table	zone_id	long
	xcoord	double
	ycoord	double

Table 3: Constructed output tables from an UrbanSim zone application for MATSim.

4.1.3.2 *MATSim output*

This section looks at the feedback indicators from MATSim to UrbanSim that will be implemented. At this point, the terms access and accessibility are defined to provide a common communication basis:

The term *access* refers to a two-point-value such as travel time impedances between an origin-destination (OD) pair; in contrast, *accessibility* is attached to one location and thus refers to an aggregated single-point-value.

The following provides a brief summary about the planned MATSim feedback:

zone-to-zone impedance matrix The impedance matrix is an origin-destination-matrix (OD-matrix) including travel times and generalized travel costs for any pair of zones.

Planned feedback indicators include travel times for several transport modes, travel distances, generalized costs of travel and vehicle trips.

Travel times will be provided for congested and free speed car, public transport, bicycle and traveling on foot. Travel distances will refer to the shortest path on the road network. Generalized travel costs are computed as utility including congested car travel times, distances and toll as given by Eq. 9. Vehicle trips will be obtained from the selected plan of each executed agent, e.g., see Sec. 3.3. The number of trips will be scaled to 100% when smaller population sample sizes are used.

agent-based performance This will feedback the travel performances for individual agents based on their selected plan, e.g., see Sec. 3.3. The output will include the selected transport mode, e.g., car or public transport, including the respective travel times and travel distances for both directions, i.e., commuting from home to work and back.

accessibility A comprehensive description about accessibility computations in MATSim at high resolutions is provided in Ch. 6. At this point, only a brief overview is provided.

Various accessibility measurements exist. In this thesis, a utility-based measurement is selected [e.g., Ben-Akiva and Lerman, 1985; Train, 2003] which is also known as the logsum. It reflects the (economic) benefit, as the maximum expected utility, that someone gains from access to spatially distributed opportunities [Geurs and Ritsema van Eck, 2001; de Jong et al., 2007]. The logsum is used as a policy evaluation measure [e.g., de Jong et al., 2007]. It can be seen as a proxy for other accessibility indicators.

Accessibilities will be calculated at different spatial resolutions such as zones and grid-cells as well as for different transport modes. For UrbanSim zone applications, MATSim calculates accessibilites using the zone-based approach, which determines and returns accessibilites on the zone level. For UrbanSim parcel applications the cell-based approach is used. Once the calculation for each cell is completed MATSim interpolates accessibility value from the grid-cell for each UrbanSim parcel. Supported transport modes are congested and free speed car, public transport, bicycle, and traveling on foot.

4.2 cold, warm and hot start

One objective of coupling MATSim with UrbanSim is to provide the so-called *warm start* capability in order to reduce computing times for the travel model.

This section summarizes relevant aspects to achieve this goal and explains how this can be achieved and implemented. In addition, hot start, another approach to reduce computing times for the travel model is presented.

This section is structured as follows. The next section summarizes aspects that are relevant in this context. Sec. 4.2.2 introduces the terms *cold*, *warm* and *hot start* and looks into the implementation. Three scenarios are created to investigate savings in computing times. Details on the data and configuration settings are summarized in Sec. 4.2.3. The simulation approach and results are presented in Sec. 4.2.4. This section is concluded by a discussion and conclusion.

This section is a derived version of Nicolai [2013].

4.2.1 *Introduction*

At this point, a closer look into the interaction between MATSim and UrbanSim is taken in order to provide an understanding of how computing times for the traffic simulation can be reduced. The interaction sequence was already described in Sec. 4.1.1. The following summarizes the demand generation and the iterative demand optimization process in MATSim, which are the relevant parts in this context.

Each time MATSim is called by UrbanSim, it receives the population with the current land use such as the residence and work location for every person. Each person or traveler is modeled as an individual agent in MATSim. The demand of an agent is called plan (see Sec. 3.3), which encodes the daily routine of an agent such as routing decisions from home to work and back, mode choice or departure times. The iterative demand optimization process, described in Sec. 3.5, improves the demand individually for each agent. It consists of an iteration cycle with three main steps – *Execution*, *Scoring* and *Re-planning*. Usually, the iteration cycle is allowed to continue until a *relaxed* state of the system has been reached [Balmer et al., 2005a, p.98]; however, there is no quantitative measure of when this state is reached [Balmer et al., 2005a, p.98]. According to [Balmer et al., 2009b, p.70] a relaxed state is reached when "the utility for each agent does not noticeably change through variation of the day plans" and "the trajectory of average utility per iteration represents a stationary process" – the underlying scoring function is explained in Sec. 3.6.

In other words: Each time MATSim is called, the demand optimization process for each agent starts from scratch, even if nothing has changed for the agent in the land use model; for instance the residence and work location are the same. In order to reduce the number of iterations of the optimization process and, thus, the computing times for the traffic simulation, it is reasonable to identify these agents and to reuse their plans.

The next section describes in detail how this can be achieved.

4.2.2 *Implementation*

At this point, three notations are introduced: cold, warm and hot start.

COLD START This was in principle described in the previous section. It means that MATSim generates the initial travel demand based on the provided UrbanSim population and current land use as explained in Sec. 4.1.1. This is illustrated in Fig. 9.

WARM AND HOT START Warm and hot start are describing the capability of MATSim to start a simulation from a pre-existing, relaxed plans file to recycle information, e.g., route, transport mode and departure time choices, from previous MATSim runs. In other words, MATSim "remembers" the travel schedule (daily plan) of each traveler. Consequently, fewer iterations are and thus less computing time is required to reach a relaxed state of the system.

The difference between warm and hot start is given by the use of distinct plans files. In warm start, MATSim will always use the same relaxed *initial plans* file as shown in Fig. 9. However, when running UrbanSim over many years with a changing population, e.g., due to relocation of households and firms, the initial plans file will become less and less correct and requires more and more iterations to get MATSim back into a relaxed state. This issue is addressed by hot start. Here, MATSim stores an *updated plans* file after each run that incorporates all changes of the current UrbanSim population. As a result, differences between the updated plans file and the UrbanSim population of a subsequent year (UrbanSim iteration) are kept small. As opposed to warm start, MATSim uses the updated instead of the initial plans file with hot start as shown in Fig. 9.

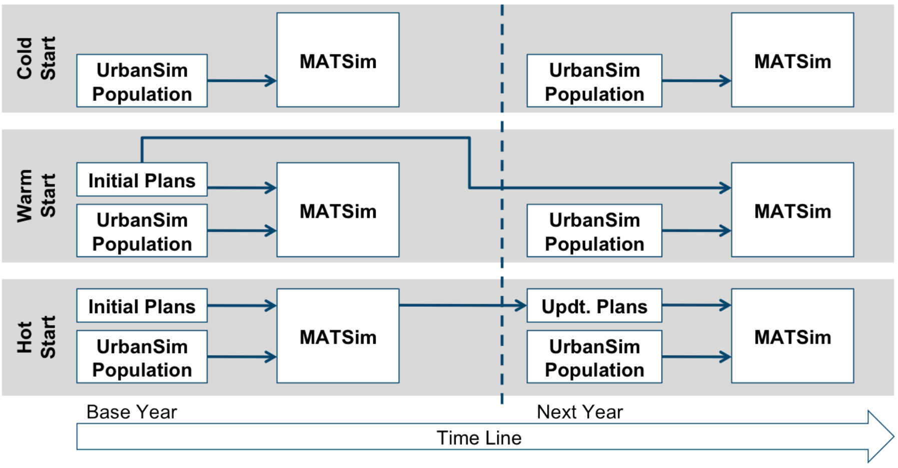


Figure 9: This illustrates the working of the (i) cold, (ii) warm and (iii) hot start in MATSim. With (i) cold start, MATSim generates the initial demand from the current UrbanSim population. With warm and hot start, MATSim recycles information from previous runs; as a result less iterations are required to reach a relaxed state of the system. (ii) Warm start will always use the same plans file which becomes less and less correct when running UrbanSim over a long time span. Opposed to warm start, (iii) in hot start after each run an updated plans file is stored and incorporates changes from the current the UrbanSim population. In this case, MATSim starts from the updated plans file instead of the initial plans file.

IMPLEMENTATION Technically, when MATSim performs a warm or hot start it reads a plans file together with the current UrbanSim population and compares them. When converting the current UrbanSim population into MATSim agents the person IDs from UrbanSim are taken. Thus, UrbanSim persons can be individually identified among the MATSim agents via their person ID.

MATSim keeps all plans or persons from the initial plans file that have not changed. In order to determine this, the following decision tree is applied for each person:

1. A person from the current UrbanSim population exists in the plans file, i.e., an agent plan with the same person ID exists in the plans file.

2. The person has the same employment status.

3. The person has the same home location.
4. And, if applicable, the person has the same work location.

If one of this points did not apply, a new plan is generated.

4.2.3 *Scenario: Zurich, Switzerland*

The cold, warm and hot start capability of MATSim is now applied to a real-world scenario. This is the city of Zurich, Switzerland, an UrbanSim parcel-based application. A detailed description is provided in Sec. 6.3. At this point, only a brief overview is provided.

POPULATION AND TRAVEL DEMAND In order to speed up computation times, MATSim considers a 10% random sample of the synthetic UrbanSim population consisting of 33'629 agents. All MATSim agents have complete day plans with "home-to-work-to-home" activity chains. Work activities can be started between 7 and 9 o'clock, and have a typical duration of 8 hours. The home activity has a typical duration of 12 hours and no temporal restriction.

NETWORK AND ADJUSTMENTS A revised Swiss regional planning network [Vrtic et al., 2003; Chen et al., 2008] is used that includes major European transit corridors as depicted in Fig. 35. The network consists of 24'180 nodes and 60'492 links.

In order to achieve a better resolution at the urban scale, some modifications on original regional planning network have been made. In addition, the network flow and storage capacities are adjusted automatically based on the selected population sampling rate. A comprehensive description explaining these adjustments is provided in Sec. 6.3.2.

PREPARATORY MATSIM RUN A preparatory MATSim run is performed based on the UrbanSim base year by running the traffic simulation for 100 iterations with a 10% random sample of the UrbanSim population. 10% of the agents perform "time adaptation", which changes the departure times of an agent, and 10% adapt their routes. The remaining agents switch between their plans. After 80% of the iterations, time and route adaptations are switched off; thus, agents only switch between existing plans.

The resulting relaxed plans file is used as input for warm and hot start runs as described in the subsequent section.

4.2.4 *Simulation runs and results*

In the present setup, UrbanSim is executed for the period from 2000 (base year) to 2010. In this period, MATSim is called for the years 2001, 2003, 2005, 2007 and 2009. MATSim uses the same re-planning configuration as for the preparatory run described in the previous section. This means 10% of the agents use time and another 10% use route adaptation the remaining agents are allowed to switch between their plans, where time and route adaptation are switched off after 80% of the iterations.

To analyze the outcomes of the MATSim cold, warm and hot start, three simulation runs are performed:

1. **Cold start**: No input plans file is provided. MATSim will run for 100 iterations.

2. **Warm start**: The plans file from the preparatory MATSim run is provided. The number of MATSim iterations are reduced to 60.

3. **Hot start**: In contrast to warm start, MATSim takes the plans file from the preparatory MATSim run only for 2001, the first time MATSim is called. In subsequent calls, MATSim uses the updated plan file from the previous run as explained above in Sec. 4.2.2. At this point, MATSim iteration are limited to 30.

The outcomes of these simulation runs for the selected years are presented in Fig. 10, 11 and 12. It should be noted that different scales regarding the score and number of iterations are used in order to better illustrate the outcomes. The plots show the score, i.e., the performance, of executed agent plans by iteration. More in-depth information about the relaxation process in MATSim is given in [Balmer et al., 2009b].

The evaluation concentrates on the performance of the executed plans that are actually performed in the traffic flow simulation.

In Fig. 10, the results for cold start are presented. It can be noticed that the average score of executed plans initially starts at a very low level. In each iteration, agents try to optimize their plans by applying the re-planning strategies as described above. Especially during the first 10 - 20 iterations the performance of the plans improves significantly. After 80 iterations, the average score of executed plans converges into a relaxed, steady state and approaches the average best score (blue line). At this point, time and route adaptation were switched off.

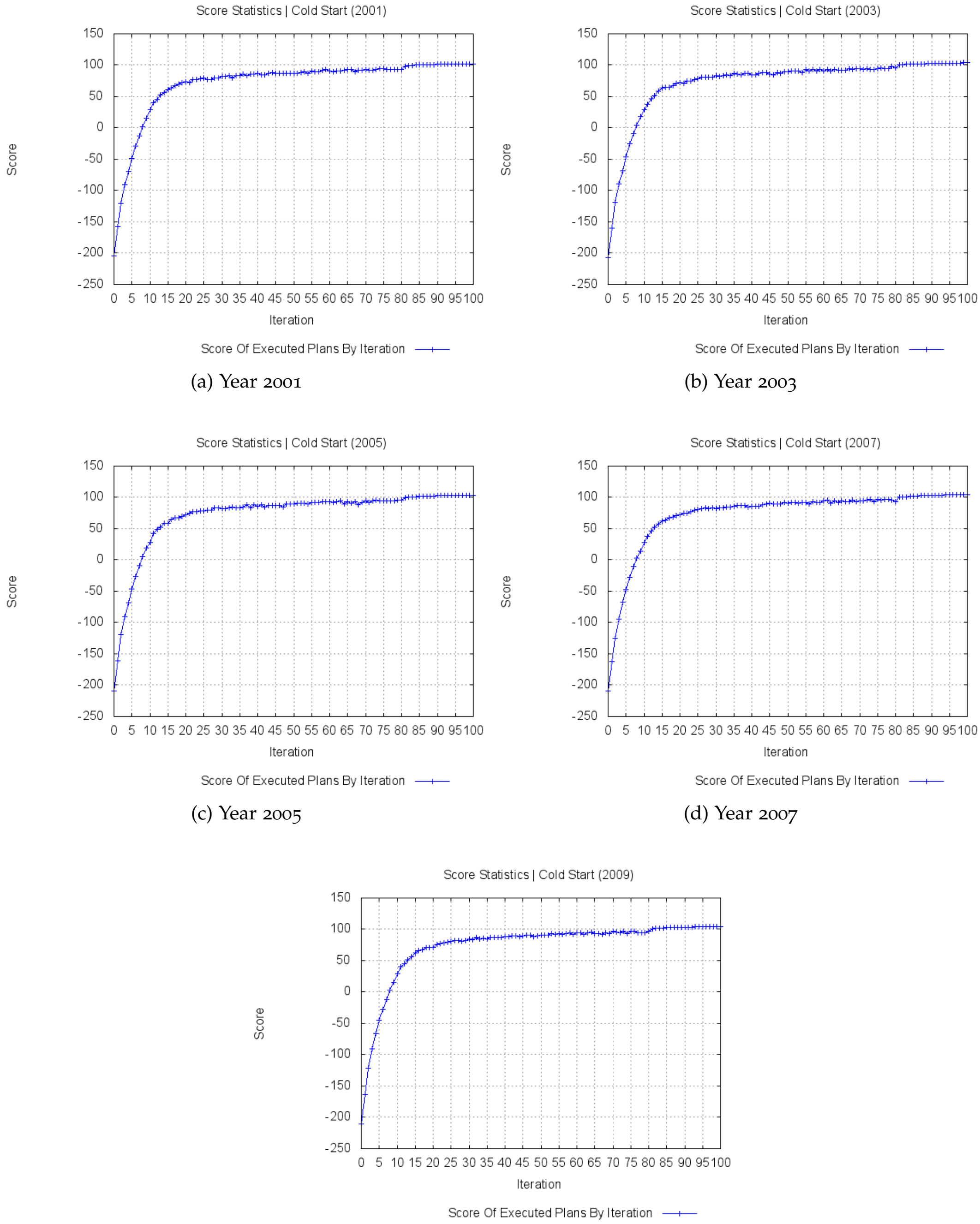
Warm start, see Fig. 11, shows a more differentiated picture. First, in 2001 (Fig. 11a) the score of the executed plans in iteration 0 is almost as high as the in iteration 60, the last iteration. In each subsequent MATSim run, the score starts at a lower level. This is due to the initial plans file which becomes less accurate over the years. Compared to cold start, less iterations are required to reach a relaxed state.

In Fig. 12, the results for hot start are shown. In contrast to warm start the score of the executed plans in iteration 0 can be considered as more stable, i.e., they do not start at a lower level in each subsequent year. This may be due to the updated plan files that are input. Moreover, even less iterations than in warm start are necessary to reach a relaxed state of the score. These few iterations can bee seen as the refinement procedure, where mainly agents that are changed or new try to optimize their plans.

At this point, the computing times for each scenario are presented in Tab. 4. For the present study, the number of iterations are reduced by about one third for warm start (60 iterations) and about two third for hot start (30 iterations) compared to cold start (100 iterations). This reduction is also reflected in the computing times.

Mode	2001	2003	2005	2007	2009	Total time
Cold start	121 min	121 min	122 min	121 min	120 min	605 min
Warm start	73 min	74 min	75 min	76 min	76 min	374 min
Hot start	41 min	41 min	41 min	40 min	40 min	203 min

Table 4: This table lists the computation times for cold, warm and hot start. All measurements are performed on a Mac Book Pro with an Intel Core 2 Duo 2.5GHz processor and 4 GB of memory.



(a) Year 2001

(b) Year 2003

(c) Year 2005

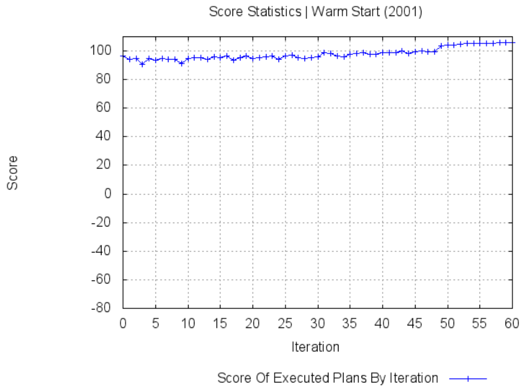
(d) Year 2007

(e) Year 2009

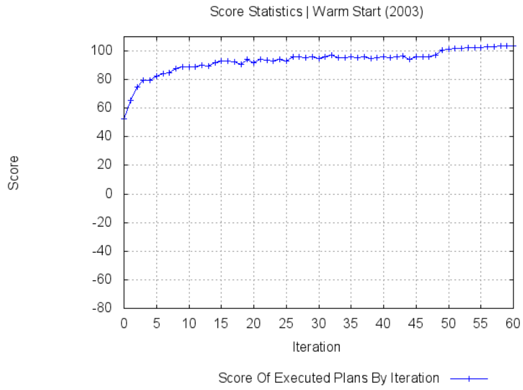
Figure 10: Cold start: These plots visualize the score (blue line) of the executed agent plans by iteration. It can be noticed that the score (performance of the plans) converges into a relaxed, steady state after 80 iterations.

4.2.5 *Discussion and conclusion*

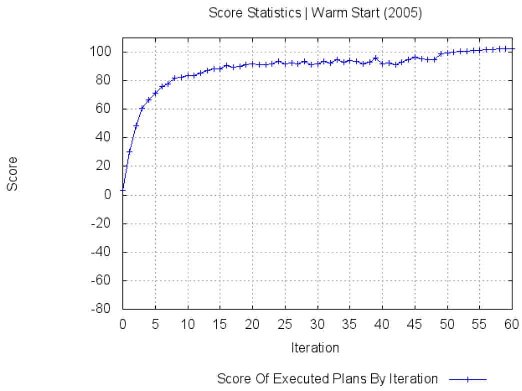
As the results show in Tab. 4, the warm and hot start require less iterations and, thus, less computing times compared to cold start in order to reach a relaxed state of the system. This is achieved by recycling agent plans or travel



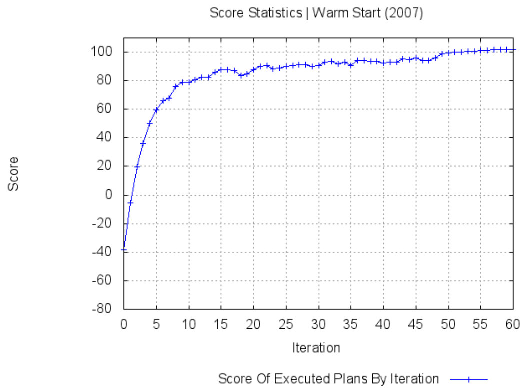
(a) Year 2001



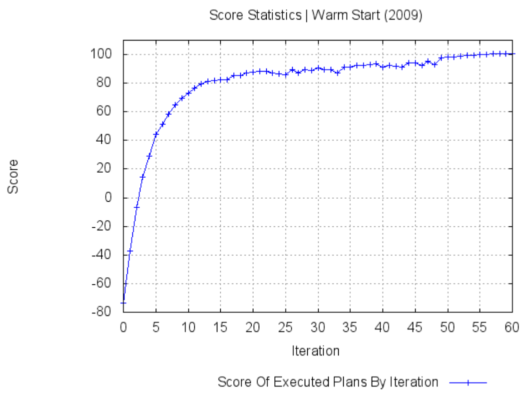
(b) Year 2003



(c) Year 2005



(d) Year 2007

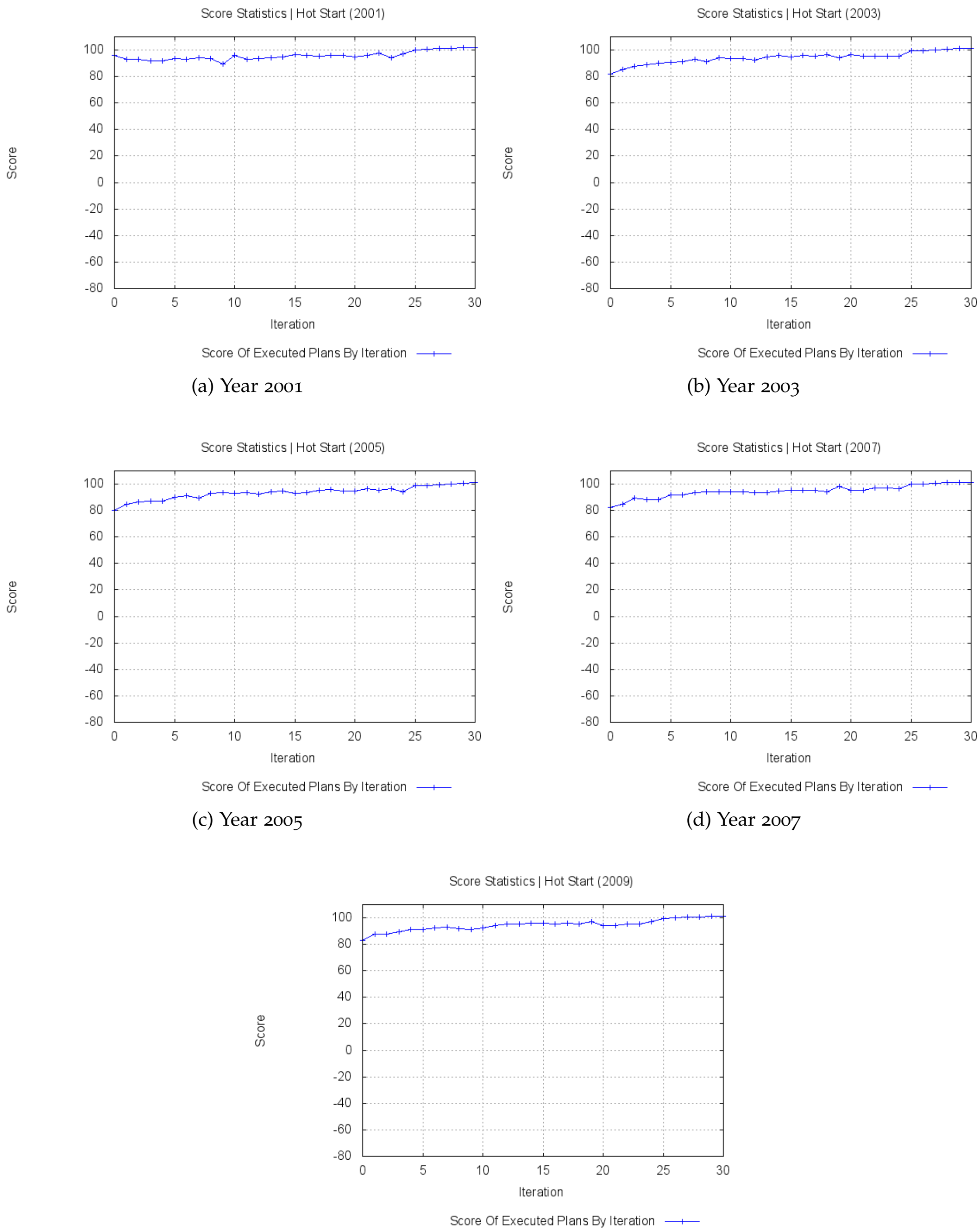


(e) Year 2009

Figure 11: Warm start: These plots visualize the score (blue line) of the executed agent plans by iteration. In each subsequent MATSim run, the score (performance of the plans) starts at a lower level which indicates that the initial plans file becomes less and less correct. Fewer iterations (50 iterations) compared to cold start is required to reach a relaxed, steady state of the system.

schedules from previous MATSim runs, e.g., from a preceding UrbanSim iteration.

As already mentioned above, there is no quantitative measure of when the system reached a relaxed state. For the present study, the number of



(a) Year 2001

(b) Year 2003

(c) Year 2005

(d) Year 2007

(e) Year 2009

Figure 12: Hot start: These plots visualize the score (blue line) of the executed agent plans by iteration. The initial score (performance of the plans) always starts on a consistently high level. Less iterations compared to cold and warm start are required to reach a relaxed, steady state of the system.

iterations for each simulation run, cold, warm and hot start, are selected for illustration purposes. The required number of iterations will vary depending on the respective scenario.

For warm start, the number of iterations also depend on the time horizon of the urban simulation since the initial plans file will become less and less correct over time. In this sense hot start provides the best performance: It uses the least computing time, and computing time does not vary with the time span of the urban simulation.

5 CASE STUDY

Urban simulation models include location choice decisions of firms, residents and developers. Access to certain activity locations has an influence on these choices. The difficulty to get to locations is clearly not uniformly distributed across space, and travel models of various forms may be used to generate times or generalized costs of travel between locations.

In the past, some efforts towards integrating travel and land use models have been made. One example is the effort to couple UrbanSim with EMME [Babin et al., 1982] or VISUM [PTV AG, 2009a,b]. In that approach, UrbanSim moves forward in time from year to year calling the travel model in regular intervals. The travel model takes the urban structure as input, computes a traffic assignment, and returns a zone-to-zone impedance matrix. UrbanSim then uses that matrix as input to its location choice models. However, both EMME and VISUM are traditional assignment models using origin-destination matrices (OD-matrices) as inputs [Ortúzar and Willumsen, 2001; Balmer et al., 2005b] and do not make use of the disaggregated nature of UrbanSim.

In this situation, it seems quite natural to link micro-simulation land use models like UrbanSim with an agent-based travel model like MATSim directly at the person level, feeding location and socio-economic characteristic of individual residents and firms from the land use model to the travel model and then having the travel model return updated traffic conditions back to the land use model. At this point, a first implementation of the integrated modeling framework is used, where MATSim feeds back its results in a zone-to-zone impedance matrix. The coupling of MATSim with UrbanSim was already presented in the previous chapters (Ch. 4 and A).

In the present chapter, the integrated modeling framework will be analyzed in a case study. This is done by creating and simulating a scenario in which the accessibility of an initially poorly connected area is improved compared to the base case. Also congestion effects are investigated.

The chapter is structured as follows: In Sec. 5.1, a brief introduction is provided. The simulation approach is summarized in Sec. 5.2. Details on the data and scenario setups are presented in Sec. 5.3. Section 5.4 illustrates the main results of the simulated scenarios, which are discussed in Sec. 5.5. The chapter ends with a conclusion in Sec. 5.6.

This chapter is a derived version of Nicolai, Wang, Nagel, and Waddell [2011].

5.1 INTRODUCTION

There is some agreement that access to certain activity locations has an influence on residential and firm location choices [e.g., Vandenbulcke et al., 2009]: Hansen [1959] defines accessibility as the potential of opportunities for interaction. He showed that areas which are more accessible to certain activities like work, leisure or shopping have a greater growth potential in residential development. Moeckel [2006] asserts that this approach is also true for businesses. Accessibility measures a locations attractiveness. In other words:

Locations with easier access to other locations are more attractive compared to otherwise similar locations with less access.

In the context of land use and transport interaction (LUTI) models, accessibility is a central measurement. It measures the difficulty to reach opportunities such as workplaces, locations for shopping and leisure activities. The difficulty to travel from an origin to a destination can be described by the amount of travel time and generalized travel costs. These result from the interaction of many components [Geurs and Ritsema van Eck, 2001; Geurs and van Wee, 2004]. Two prominent components are land use and transport which are influencing each other in a dynamic and complex manner [Borzacchiello et al., 2010]: Accessibility provided by transport influences location decisions of developers, firms and households [Hansen, 1959; Moeckel, 2006] as mentioned above. Conversely, land use determines the need for spatial interaction [Wegener, 2004; Strauch et al., 2005; Wegener, 2011]. LUTI models are taking those interactions into account by combining land use and transport models with feedback mechanisms between them. For the present study, the integrated MATSim and UrbanSim framework will be used:

UrbanSim is a microscopic simulation model for urban development that includes explicit location choice models for residences, workplaces, and development. These models relay on the accessibility feedback provided by the travel model. In order to update travel conditions, MATSim computes the traffic assignment based on the current given the land use pattern and transport network and returns a zone-to-zone impedances matrix incorporating travel times and generalized travel costs as feedback to UrbanSim.

This chapter studies, through simulation runs of multiple scenarios, the impact of a very large accessibility increase, i.e., reduced travel times and travel costs, on land use and residential location choices in an existing real world scenario by using the integrated framework. The scenarios for the present study are built on the current UrbanSim application for the Puget Sound Regional Council (PSRC). In order to investigate the accessibility effect, the following scenario is hypothesized:

A slow ferry connection between Seattle downtown and the so-called Bainbridge Island is replaced by a fast bridge connection. Clearly, this development is highly artificial, and it is selected for research and illustration purposes only. However, it might be worth mentioning that in the early sixties of the last century, there were bridge construction plans that would have had a similar effect: The two bridges marked by "7" in Fig. 13 show the plan to connect Bainbridge Island with Seattle via the Cross-Sound Bridge and Rich Passage Bridge.

5.2 SIMULATION

The simulation in MATSim and UrbanSim as well as their interaction were already explained in detail in Sec. 2.6, 3.2 and 4.1. At this point, a brief summary is provided.

UrbanSim is an agent-based urban simulation model that does not model transport itself [Wegener, 2004]. It relays on the interaction with external travel models to update traffic conditions from the current land use. Some integration efforts with traditional assignment models have been made that are using origin-destination matrices (OD-matrices) as inputs [e.g., Ortúzar and Willumsen, 2001].

Figure 13: Map of proposed Puget Sound freeway plans in the early 1960s from the Washington State Highway Commission. Image courtesy of Scott Rutherford, University of Washington.

Unlike traditional assignment models, disaggregated agent-based traffic simulation models like MATSim [e.g., Raney and Nagel, 2006; Balmer et al., 2005a] simulate each traveler individually. In the present coupling approach, MATSim takes the synthetic UrbanSim population and directly simulates its travel behavior. The travel demand is, in principle, a result of individual decisions made by each agent trying to organize their day and engage activities at and out of home [Raney and Nagel, 2006; Balmer et al., 2005a]. Besides, MATSim provides additional advantages such as simulating time-dependent congestion, time-dependent mode choice, or speeding up the computation by running small samples of a scenario.

The input to the UrbanSim models includes the base year data, the access indicators from the external travel model, and control totals derived from external macro-economic forecast models. The base year data store contains the initial state of a scenario. The database includes geographic information, initial household and job information, etc., for a given base year. The primary source of the base year data usually comes from surveys or the census. The UrbanSim models reflecting the decisions of households, firms, developers and governments (as policy inputs) maintain the data store and simulate its evolution from one year to the next [Waddell, 2002].

As discussed earlier (Sec. 4.1.1), the interaction between UrbanSim and MATSim is a bi-directional relationship. When UrbanSim moves forward in annual steps, it calls MATSim in regular intervals and passes the traffic network together with the persons and jobs data set table as input including the person ID as well as the residence and job location of each individual person in UrbanSim[1]. Based on this information, MATSim generates the traffic assignment and returns a zone-to-zone impedance matrix, an illustrative example for the zone-to-zone impedance matrix is shown in Fig. 14. UrbanSim then uses this updated matrix as input to its models for its next iteration.

The zone-to-zone impedance matrix consists of times and generalized costs of travel for any pair of zones. Car travel times are calculated based on the link travel times on the congested network obtained at the end of the MATSim traffic simulation as mentioned in Ch. 3.7. Zones are connected to the road network by connecting the zone centroid to the closest link in the network. The coordinates of the zone centroid is determined by averaging over the coordinates of all parcels that belong to the same zone. In addition, also walk travel times are calculated. This is implemented provisionally in MATSim by taking the car travel times multiplied by 10. The generalized costs at this point consist of car travel time and toll (as time equivalent). Since no toll was assumed for the study here, for the purposes of the present study car travel times and travel costs are identical. Downstream models that use travel model output are listed in Tab. 5.

from_zone_id	to_zone_id	am_single_vehicle_to_work_travel_time
601	601	1.2
601	602	1.382407407
601	603	6.585138889
601	604	25.50588217
601	605	24.45122834
601	606	24.56518667
601	607	23.21328958
601	608	22.14995625

Figure 14: The standard feedback from external travel models to UrbanSim is a zone-to-zone impedance matrix. This figure provides an illustrative example of a zone-to-zone impedance matrix including travel times "am_single-_vehicle_to_work_travel_time" from any origin zone "from_zone_id" to any destination zone "to_zone_id".

5.3 SCENARIO

The coupling of UrbanSim with MATSim is now applied to an existing real-world scenario. This is the parcel-based Puget Sound region application (PSRC) which is one of the most disaggregate metropolitan-scale UrbanSim modeling systems in operation. It consists of 1'500'004 parcels and 938 zones. The simulated scenarios are briefly described in the following.

1 This implies that a "workplace choice model" is used inside UrbanSim which assigns every working person to an available job. This model is used in the UrbanSim PSRC scenario by default.

5.3.1 *Population and initial demand*

The metropolitan area of the Puget Sound region counts about 3.2 million inhabitants in the UrbanSim base year 2000 and increases to over 4.4 million at simulation end in 2030.

In this set-up, MATSim is scheduled in every of the 30 UrbanSim years from 2000 to 2029. In order to speed up computation times, MATSim considers a 1% random sample of the synthetic UrbanSim population.

All travelers (agents) in MATSim have complete day plans with "home-work-home" activity chains based on their residence and job location in UrbanSim as described in Sec. 4.1.1.

Work activities can be started between 7 o'clock and 9 o'clock. They have a duration of 8 hours. The home activity has a typical duration of 12 hours and no temporal restrictions. Each agent has five plans based with the described activity pattern and try to optimize their plans with respect to the choice dimensions available: route choice and time choice as described in Sec. 3.5.

5.3.2 *Network*

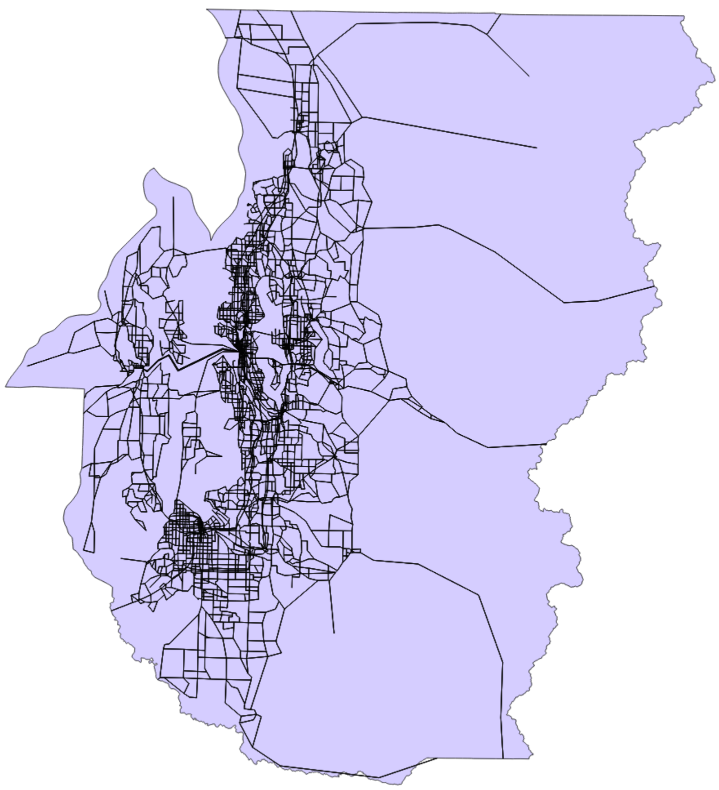


Figure 15: This show the PSRC study area (blue area) together with the MATSim network.

The Puget Sound traffic network includes the major roads in this area as depicted in Fig. 15. It consists of 5024 nodes and 15'472 links. Roads are typically described by two links, with one link for each direction. Furthermore, each link is defined by its origin and destination node, length, free speed, average car flow capacity per hour and number of lanes.

In MATSim, ferry connections are also modeled as roads. The ferry between Seattle downtown and Bainbridge Island in particular is modeled as follows: The ferry route consists of several subsections represented by links with a single lane in each direction. The narrowest link of this route has an average car flow capacity of 500 cars per hour with a free speed of 9.94 mph. The free speed of 9.94 mph is due to the conversion from metric system. The imaginary bridge construction between Seattle downtown and Bainbridge Island is described in detail in Sec. 5.3.5.

5.3.3 *Traffic simulation*

The UrbanSim modeling sequence calls the travel model at the end of an update from one year to the next. This means, in particular, that the update from 2000 (the first year of the UrbanSim run) to 2001 is based on the travel data that exists already in the travel data cache. In addition, model estimations may use travel data attributes, which also comes from the base year cache.

In consequence, in order to remain consistent it is necessary to replace the original travel data cache from the PSRC scenario by a new travel data cache from a *preparatory* MATSim run. This preparatory run takes a 10% random sample of the overall UrbanSim base year population and performs a traffic simulation with 200 iterations. During the first 100, iterations 10% of the agents perform *time adaptation* while another 10% of the agents adapt *routes*. In the latter 100 iterations agents neither adapt time nor route, but choose only between existing plans. As a result of this preparatory run, the travel data attributes “am single vehicle to work travel time”, “am single vehicle to work travel cost”, and “am walk time in minutes” are generated by the MATSim run.

5.3.4 *UrbanSim configuration*

At this point, the base year cache and configuration currently being used by Puget Sound Region Council (PSRC) is used as a starting point to construct scenarios for our simulation runs. The default PSRC base year cache is used together with the default configuration, both available on UrbanSim repository `svn.urbansim.org`, with all UrbanSim models enabled. In the following, a brief summary is provided, focusing on the main changes compared to the default settings.

1. **Replace Household Location Choice Model (HLCM)**: The HLCM from the default configuration is replaced by the HLCM specifications from Lee et al. [2010]. That model was especially designed to study effects of accessibility on residential household location choices. Therefore, it is useful for the needs for this study. Instead of the accessibility variables used by [Lee et al., 2010], a simpler variable is used, measuring the generalized cost to get to Seattle CBD (Central Business District) “lngcdacbd bldg”.

2. **Replace relevant travel data attributes by MATSim**: In the next step it is tested which travel model attributes are actually used in UrbanSim. For this, all model specifications from the base year cache were manually investigated. An overview can be found in Tab. 5.

   Some of the travel model attributes in Tab. 5. are already replaced and updated by MATSim, see Sec. 5.3.3. This means that the other

Travel Data Attribute	Affected UrbanSim Models
am single vehicle to work travel time [in min]	Real Estate Price Model Expected Sales Price Model Household Relocation Model Work at Home Choice Model
single vehicle to work travel cost [in min]	Real Estate Price Model Expected Sales Price Model Employment Location Choice Model Household Location Choice Model
am walk time [in min]	Real Estate Price Model Expected Sales Price Model
am total transit time walk → removed	Real Estate Price Model Expected Sales Price Model
am pk period drive alone vehicle trips → removed	Real Estate Price Model Expected Sales Price Model
logsum hbw am income 1 – 4 → removed	Workplace Choice Model for Residents
single vehicle to work travel distance → replaced by "am single vehicle to work travel time"	Workplace Choice Model for Residents

Table 5: Travel data attributes that are used inside the UrbanSim PSRC parcel model. The attributes in boldface are replaced by MATSim output. The other attributes are either removed from the model specifications, or replaced by other attributes as indicated in the table. In all cases, models which use travel data attributes are re-estimated.

travel data attributes remain unchanged. Since these other attributes, however, are also related to the congestion computed by the travel model, they are removed from the UrbanSim model by the following steps: (i) Attributes in the base year cache that are not replaced by MATSim are deleted from the base year cache; (ii) UrbanSim model variables based on these attributes are either removed from the model specifications or replaced by travel model attributes that are actually computed by MATSim, which are presented in Tab. 5.

3. **Model re-estimation**: After adjusting the base year cache and model specifications, the UrbanSim models are re-estimated. The estimation results for the HLCM are presented in Tab. 6. A comprehensive explanation of each HLCM variable can be found in Lee et al. [2010, Sec. 4.2].

Variables and Description	Estimate	t-values

Continued on next page

Variables and Description	Estimate	t-values
ln residential units Log of number of residential units in building	-0.314	-11.513
same area type (dummy) Building in same area type as previous household (HH) location	5.124	3.782
same area (dummy) Building in same area as previous HH location	6.990	4.480
Kitsap (dummy) Building in Kitsap County	0.1651	0.0845
population density Log of zonal population density	-0.004	-0.103
disposable inc Log of HH annual income (inc) less annual imputed rent/unit	0.012	0.765
high inc (dummy) x size High HH inc x log of average dwelling size (sq ft/unit)	0.270	2.413
mid inc (dummy) x size Mid HH inc x log of average dwelling size (sq ft/unit)	-0.234	-2.541
low inc (dummy) x size Low HH inc x log of average dwelling size (sq ft/unit)	-0.190	-1.546
inc x condo (dummy) Log of HH inc x condominium	-0.111	-8.512
inc x mfr (dummy) Log of HH inc x multifamily residential (MFR) building	-0.247	-19.430
one pers (dummy) x not sfr (dummy) one-person HH x not single-family residential (SFR) building	0.485	3.990
renter (dummy) x mfr (dummy) Renting HH x MFR building	2.927	18.640
kids (dummy) x SFR (dummy) HH with children x SFR building	1.572	8.146
kids (dummy) x kids HH with children x percent HH with children within 600m	0.0056	0.861
young (dummy) x young HH Young HH (average adult age $\leqslant$ 30) x	0.050	2.520

Continued on next page

Variables and Description	Estimate	t-values
percent young HH within 600m		
lngcdacbd bldg	-0.246	-3.562
Log of generalized costs to get to CBD		
Log-likelihood	-3541.052	
Null Log-likelihood	-14978.873	

Table 6: Results of the Household Location Choice Model (HLCM) re-estimation. Explanation of HLCM variables from Lee et al. [2010].

5.3.5 *Simulation runs*

Three scenarios, a base scenario and two alternative scenarios, are created to analyze the integration of MATSim into UrbanSim. These scenarios differ only in the network set-up.

1. **Base Scenario (*Ferry*)**: The base scenario, also called *Ferry* scenario, leaves the traffic network as it is. In particular the ferry connection between Seattle downtown and Bainbridge Island remains, i.e., the corresponding links of this connection have a capacity of 500 travelers/hour with a free speed of 9.94 mph.
2. **Alternative Scenario 1 (*Bridge*)**: In this scenario the ferry connection from the base case is replaced by a bridge, hence this is the *Bridge* scenario. The bridge is simulated by setting the free speed of the ferry connection from 9.94 mph to 70 mph. The free speed is derived from the speed limits on highways in Washington (state) to simulate a fast connection.
3. **Alternative Scenario 2 (*Capacity Limited Bridge*)**: The ferry connection here is replaced as well by a bridge. Besides a free speed 70 mph, the capacity of the links are reduced dramatically from 500 to 50 travelers/hour. Hence, this bridge can be described as a fast but capacity-limited connection that is susceptible to congestion.

The traffic connection in the first two scenarios provides enough capacity, i.e., 500 travelers/hour, to manage the traffic peaks between 6 and 7 o'clock and between 16 and 18 o'clock for the year 2001 where the bridge is available for the first time. The *Capacity Limited Bridge*, with a capacity of only 50 travelers/hour, cannot handle these peaks: It takes several hours to process them. Hence, this connection is congested, which results in longer travel times. In UrbanSim, the travel model is run at the end of an UrbanSim iteration. In consequence, the modified networks are used for the first time after the iteration from 2000 to 2001. One could say that the bridge construction in these scenarios is finished in 2001 and operational in 2002.

5.4 RESULTS

In the following, the simulation results for Bainbridge Island, which has the UrbanSim zone number 908, are presented. All plots refer to the three scenarios *Ferry* (red line), *Bridge* (blue line) and *Capacity Limited Bridge* (green line).

5.4.1 *Travel and accessibility consequences*

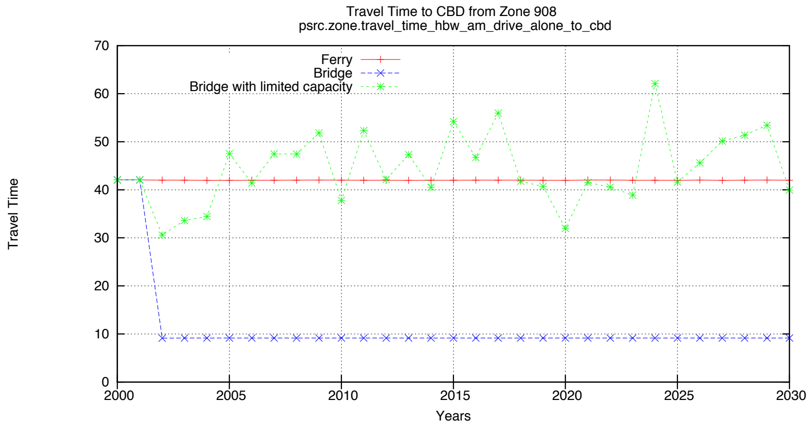


Figure 16: Travel Time from Bainbridge to Seattle CBD.

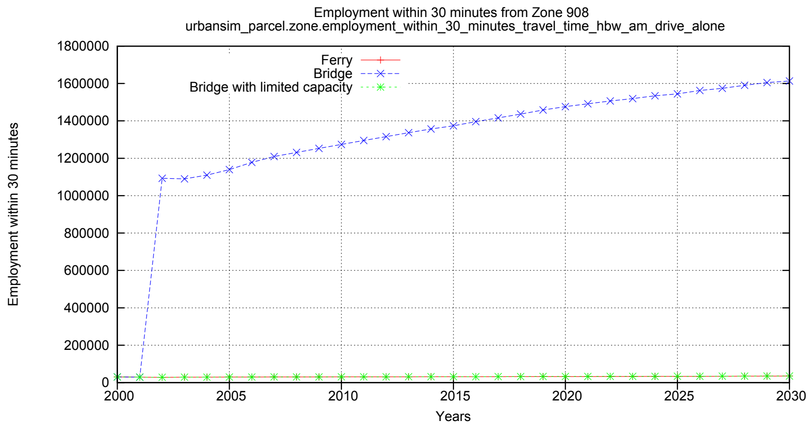


Figure 17: Reachable number of employment within 30 minutes of car travel from Bainbridge.

The travel time from Bainbridge Island to Seattle CBD (Fig. 16) in the *Ferry* scenario remains constant at about 40 minutes. In the *Bridge* scenario it goes to below 10 minutes. In the limited capacity scenario it fluctuates rather strongly. This is presumably a consequence of stochastic effects in the travel model that should be investigated further.

A direct influence of the travel time is visible in the Employment-within-30-minutes plot (Fig. 17): Clearly, shorter travel time to given destinations lead to a higher number of accessible workplaces. Since the travel times in the *Ferry* and *Capacity Limited Bridge* scenario do not fall below 30 minutes, no changes for either scenario can be seen in this plot. The increasing numbers in the *Bridge* scenario are due to the increase of the number of workplaces in the Seattle CBD.

5.4.2 *Housing price consequences*

In the PSRC implementation of UrbanSim, housing prices react directly to accessibility changes. It therefore makes sense to discuss these aspects directly here before looking at other consequences.

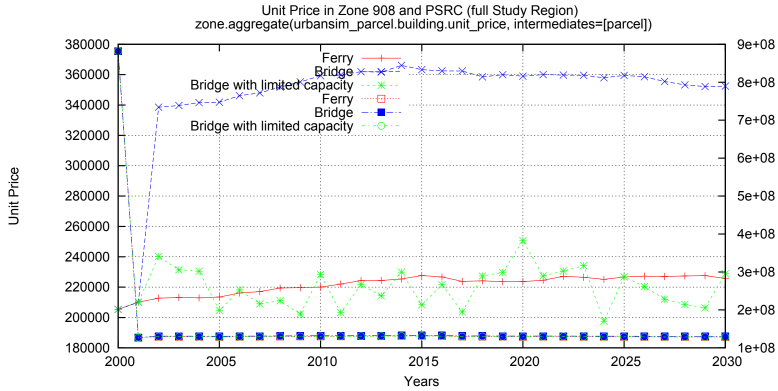


Figure 18: Unit Prices on Bainbridge (crosses) and in the full study region (squares).

The unit prices on Bainbridge are almost complementary to the travel times (Fig. 18): At the opening of the bridge in 2001 the unit prices go up sharply in the *Bridge* scenario. Also the noise of the *Capacity Limited Bridge* scenario can be found here again. Any increase of the travel time leads to falling unit prices and vice versa. The prices in the *Ferry* scenario remain almost constant analogously to the travel time.

5.4.3 *Other consequences*

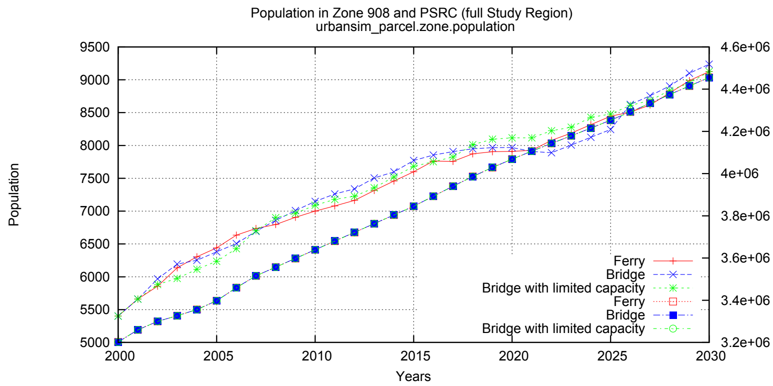


Figure 19: Population growth on Bainbridge (crosses) and in the full study region (squares).

Somewhat unexpectedly, there seem to be no population growth consequences of the increased accessibility (Fig. 19). Also the composition of households reveals no differences, e.g., in the proportion of workers and single-person households (not shown). However, the average income per person is higher in the *Bridge* scenario, see Fig. 20.

The “dent” in population growth in all three scenarios around 2020 can be traced back to the stop of the construction of the single-family residential (SFR) units (Fig. 21), which is followed only with some delay by the construction of multi-family residential (MFR) units (Fig. 22). Presumably, the UrbanSim household location choice model prefers SFR over MFR units in

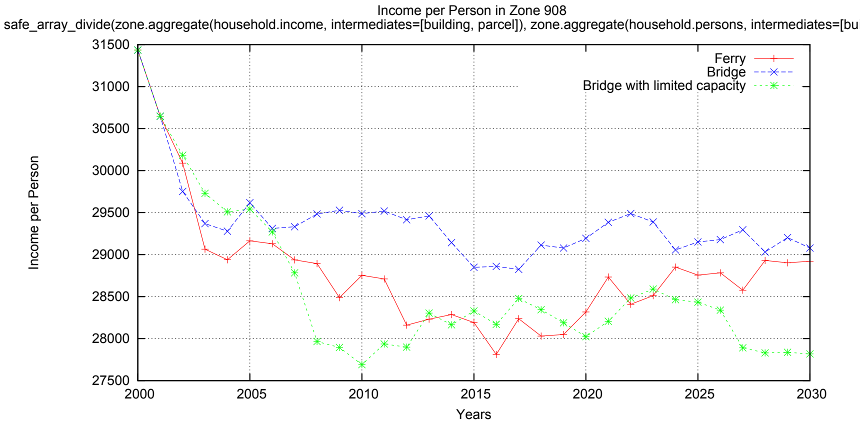


Figure 20: Income per person on Bainbridge Island.

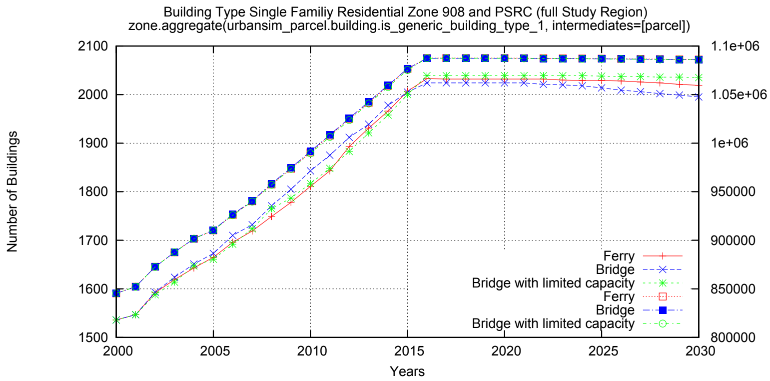


Figure 21: Single-family residential (SFR)) units on Bainbridge (crosses) and in the full study region (squares).

the present setting, and MFR construction does not start before all land with SFR zoning is exhausted.

This is corroborated by the number of vacant SFR units (Fig. 23), which shows that construction of MFR units starts exactly when all vacant SFR units are exhausted. In addition, this plot contains a difference between the scenarios: There are considerably fewer vacant SFR units available in any year after the bridge opening.

The sequence of SFR and MFR construction work can be explained by the so-called target vacancy rate that specifies the acceptable vacancy rate per building type, e.g., SFR's and MFR's, and year for the full PSRC study region. When vacancies fall below the target rate, new developments for the respective building type are triggered either until the target vacancy rate is reached, or the land with the corresponding zoning is exhausted. The predefined target vacancies and actual vacancy rates of the *Ferry* and *Bridge* scenario are presented in Fig. 24 for SFR and in Fig. 25 for MFR units [2]. The plots start from 2001. This is the first year from which the target vacancy rate is defined. For SFR units, the actual vacancy rate falls below the target vacancy rate in any year and any scenario. For MFR units this applies for 2020 when no land with SFR zoning is available as mentioned above.

2 The vacancy rates for the *Capacity Limited Bridge* scenario could not be processed.

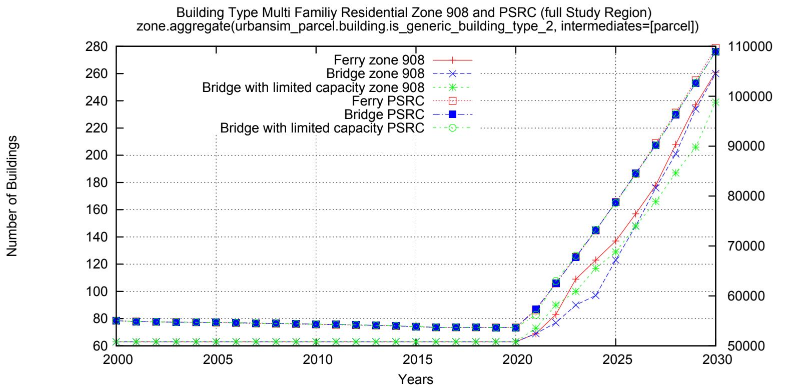


Figure 22: Multi-family residential (MFR) units on Bainbridge (crosses) and in the full study region (squares).

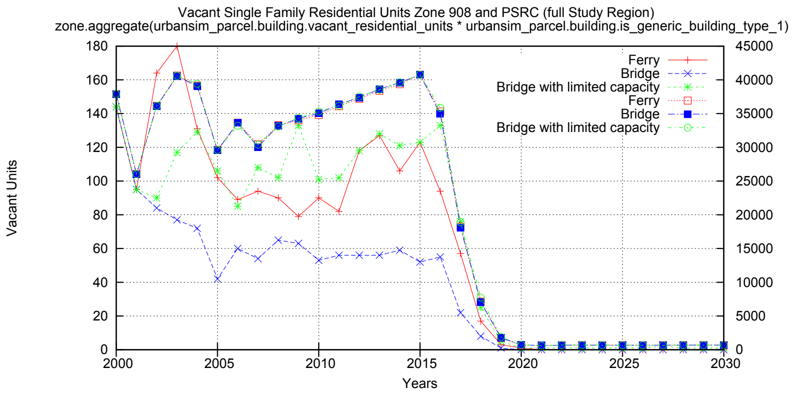


Figure 23: Vacant single-family residential units on Bainbridge Bainbridge (crosses) and in the full study region (squares).

The situation with respect to SFR units, MFR units and vacant SFR units is similar for the whole PSRC scenario, indicating that we see a property of the scenario rather than a special property of zone 908. With respect to population, zone 908 is ahead of PSRC as a whole until 2020. This may indicate that zone 908 is initially perceived as more attractive, but once it runs out of SFR units, it is more attractive to obtain an SFR unit elsewhere, and only after all SFR units are exhausted, population growth resumes in zone 908, now based on MFR units.

The remaining building types are commercial, government, industrial, office and other buildings like parking garages. Compared to the residential buildings, their numbers are small on Bainbridge Island, and there are few, if any, differences between the scenarios. They are therefore not depicted here.

It can be stated that no additional construction activities are triggered by the accessibility increase. The reason for this is the Development Project Proposal Choice Model (DPCM) that determines development projects to be constructed. More in-depth information on the DPCM is provided in [Wang and Waddell, 2010]. At this point, a brief summary is provided.

The DPCM evaluates each parcel i of the full PRSC study area and creates a set of development proposals j, e.g., buildings of different types, that are

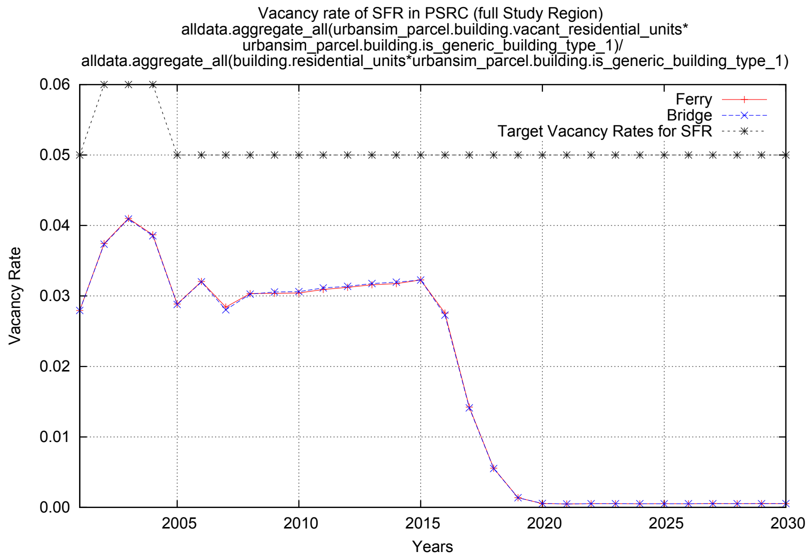


Figure 24: This shows the actual vacancy rates and predefined target vacancy rates for single family residential (SFR) units in the full study region. Vacancy rates in both scenarios *Ferry* and *Bridge* are similar. In each year, they fall below the specified target vacancy rate, which triggers new developments of SFR units until all land with SFR zoning is exhausted.

matching given parcel and land use constraints such as property type, lot size and density. The choice probability of selecting a development project, i.e., the combination of a development site i and proposal j, is consistent with random utility maximization theory [Wang and Waddell, 2010, p.5].

Each development project is weighted with the expected rate of investment (ROI) given as $roi = profit/investment$. At his point, development projects include allowed but also large number of unprofitable development proposals. Thus, the average ROI is negative. In zone 908, the average ROI for proposed development projects is almost the same in any scenario as shown in Fig. 26. For the *Bridge* scenario it is found that the average profit is higher (Fig. 27), but also the average investment costs are increased (Fig. 28).

The main reason for this can be attributed to the increased unit prices. On the profit side (given as $revenue - investment\ cost$), this leads to higher revenues or sales prices as depicted in Fig. 29. On the investment side (defined as $acquisition\ cost + demolition\ cost + construction\ cost$), higher unit prices result in higher acquisition costs (Fig. 30) to buy property or parcel in order to build on, which are mainly responsible for increased expenditures. At least for the present DPCM in the present setup, the increased accessibility is of no advantage to build more on Bainbridge.

5.5 DISCUSSION

For the PSRC implementation of UrbanSim, even drastic accessibility changes have little impact on construction activity or population growth.

A reduced number of vacant single-family units and higher incomes show the increased attractiveness of the location in spite of the now much higher prices, but this does not trigger additional construction activities.

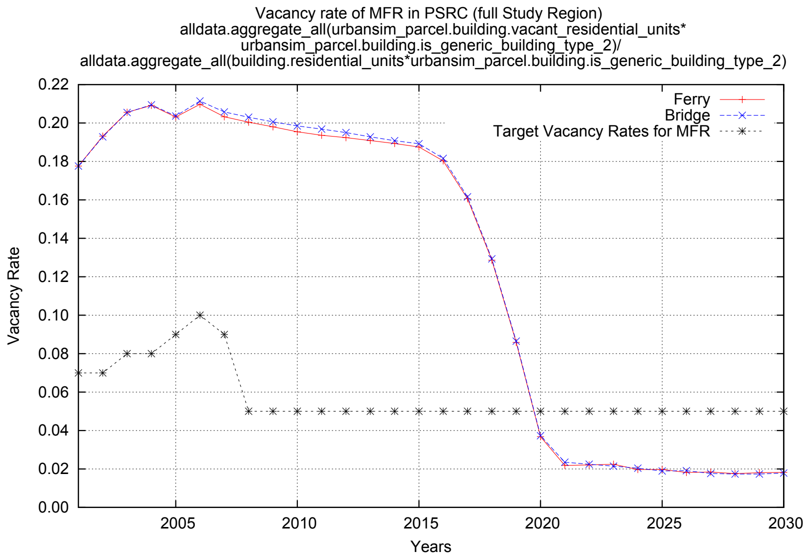


Figure 25: This shows the actual vacancy rates and predefined target vacancy rates for multi-family residential (MFR) units in the full study region. Vacancy rates in both scenarios *Ferry* and *Bridge* are similar. In 2020 they fall below the specified target vacancy rate, which triggers new developments of MFR units until all land with MFR zoning is exhausted.

At least for the Development Project Proposal Choice Model used in present setup, there is no advantage from a developer's perspective to increase construction activities on Bainbridge Island. Higher unit prices lead to both higher sales prices and also to higher investment costs, which cancel each other out. As a consequence of similar construction activities on Bainbridge, the population growth is close together in all scenarios.

There is evidence that there can also be demographic reactions to accessibility changes: In an earlier version of this study, the accessibility variable referred to single-person households only, and accordingly the share of single-person households increased significantly after the bridge opening. That model, however, was ultimately rejected since it was not considered realistic in later PSRC work [see, e.g., Lee et al., 2010].

5.6 Conclusion

This study investigates how the land use in a single zone within the modeling system UrbanSim reacts to a very large accessibility increase in that particular zone. For this purpose, MATSim4UrbanSim is used that integrates MATSim as a travel model plug-in into UrbanSim. The travel model is used to generate times and generalized cost of travel between locations. The simulation runs of multiple scenarios for the Puget Sound region illustrated the applicability of MATSim4UrbanSim to large-scale scenarios.

Rather than a synthetic scenario, a real world scenario together with an existing real-world UrbanSim implementation is used; this is done to ensure that the configuration of UrbanSim is close to a real-world implementation. The selected scenario itself, however, is highly artificial and selected for research and illustration purposes only: The replacement of a slow ferry with

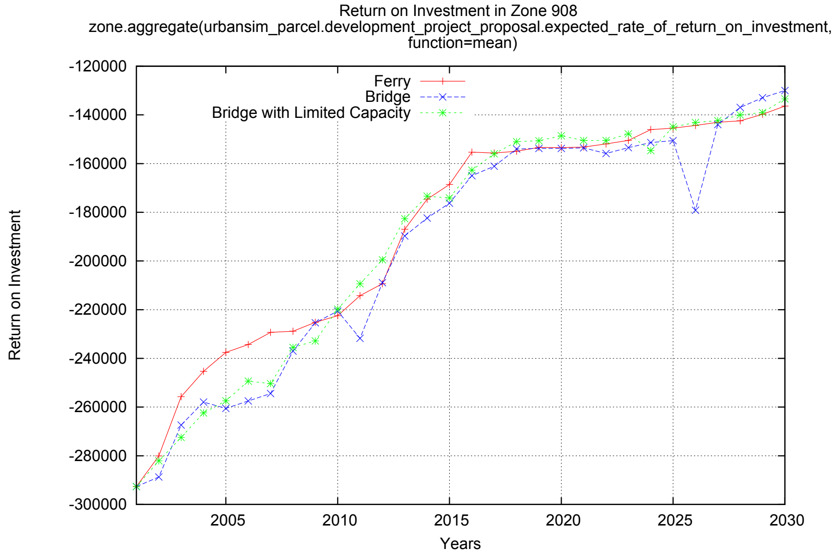


Figure 26: Average rate of return on investment for proposed development projects in zone 908.

a fast bridge connection between a central business district (CBD) and a tranquil residential area ("zone 908").

All accessibility indicators, including "reachable number of employment within 30 minutes", react strongly to the accessibility change. The accessibility change implicates dramatically lower travel times to get to the CBD together with a very high increase of accessible workplaces within 30 minutes of car travel.

Also, the price of a housing unit in the model reacts directly: It increases from $200'000 to a little more than $350'000. Despite higher unit prices, the demand for single-family residential units and the average income is considerably higher after the bridge opening. This shows an increased attractiveness of the location. But from here on, the influence of the accessibility improvement is weakening. The growth of the number of residential units is quite similar in all scenarios. No additional construction activities are triggered by the accessibility increase. This is due to the higher unit prices which affects both the sales price and investment cost in order build a new building. Thus, from a developer's perspective there is no advantage to increase construction activities on Bainbridge Island. Presumably as a consequence of the limited construction activity, also demographic indicators, meaning population growth and the composition of households, are close together in all scenarios. Again, no impact of the changed accessibility can be observed.

In addition, a *Capacity Limited Bridge* scenario was run. With this scenario, the free speed travel time from the island to the central business district is significantly reduced in principle, but because of congestion effects, the effect is dampened. In general, it fluctuates around the level of the *Ferry* scenario. Overall, this scenario lies between the other two.

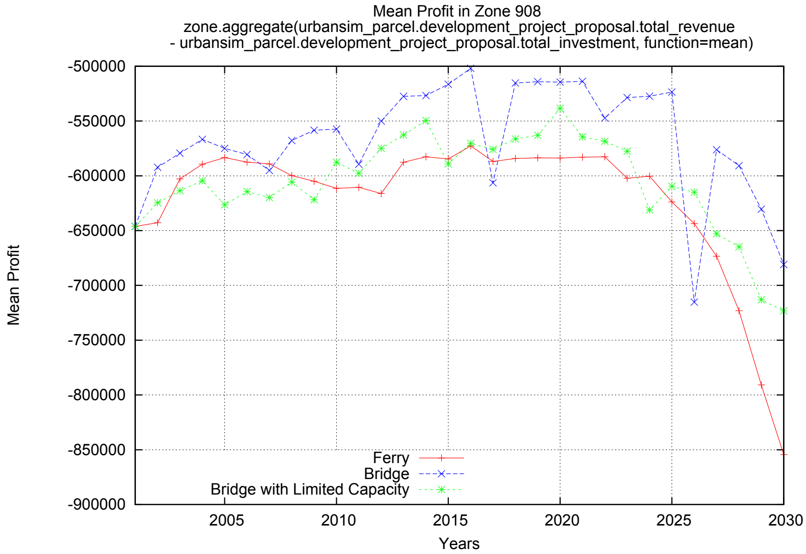


Figure 27: Average profit for proposed development projects in zone 908.

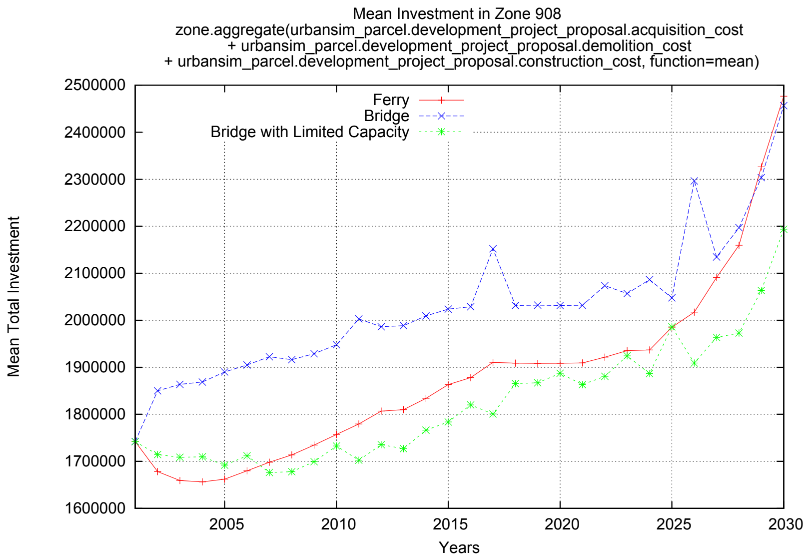


Figure 28: Average investment for proposed development projects in zone 908.

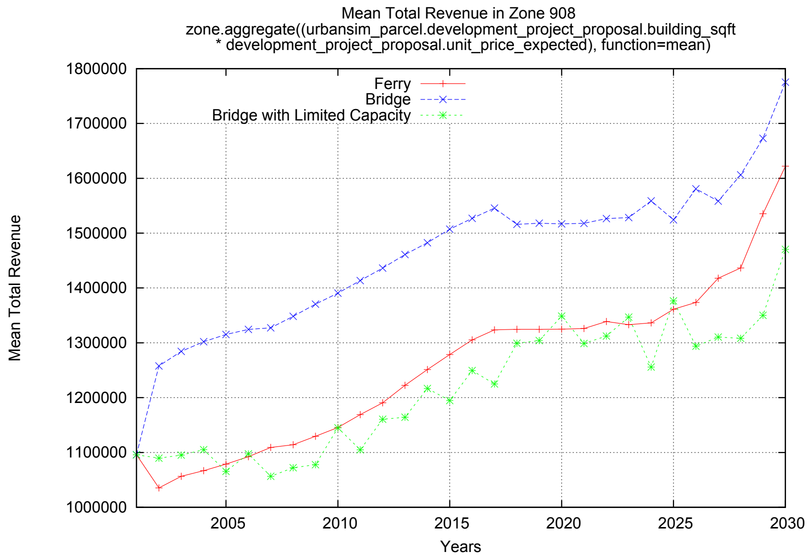


Figure 29: Average revenue for proposed development projects in zone 908.

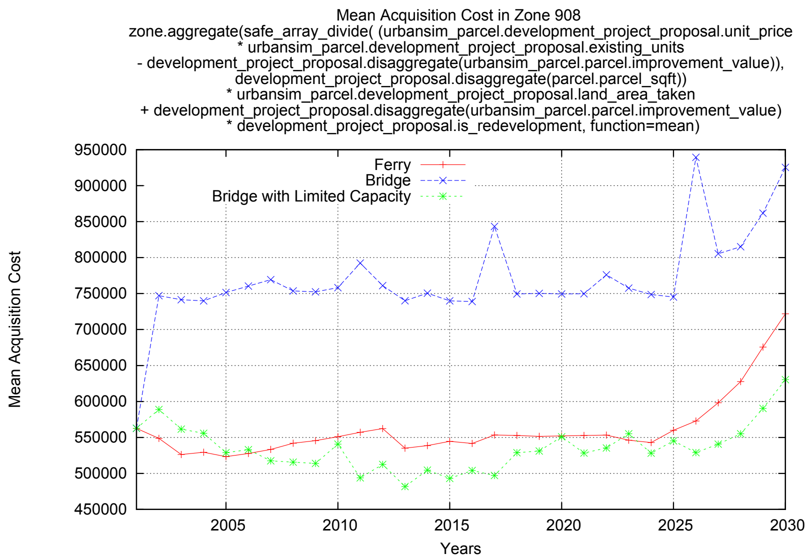


Figure 30: Average acquisition cost for a property or parcel to build a new building in zone 908.

6 THEORETICAL PRINCIPLES, IMPLEMENTATION AND ILLUSTRATIONS

As discussed earlier, UrbanSim computes location decisions are based on many attributes; some of them are related to traffic. The previous chapter presented a first case study where MATSim was used as an external travel to update the traffic conditions in UrbanSim. At this point, MATSim implements the standard feedback from external travel models to UrbanSim which is a zone-to-zone impedance matrix including generalized costs of travel for any given pair of zones (see Sec. 5.2). However, this approach has some limitations [Nicolai and Nagel, 2011]:

The feedback consists of an $n \times n$ matrix, where n is the number of zones. Such matrices are growing quadratically with the number of zones and thus quickly become very large: A typical number of 10'000 zones leads to $10'000^2 = 100'000'000$ entries; if each of them is represented as a 8 Byte floating point number, this results in $8 \times 100'000'000 = 800$ MB of memory. Although this size is still manageable, it does not leave much room for additional information such as separate matrices for different times of day or by transport mode. An additional aspect to be mentioned is the spatial resolution of the impedance matrix that is on a zone level and thus does not provide much detail. It therefore makes sense to look for alternative measurements.

The present chapter looks at the question in how far accessibility measurements can be used for this purpose. At this point, the terms access and accessibility are defined as follows: The term *access* refers to a two-point-value, such as travel time impedances between an origin-destination (OD) pair, which leads to a feedback with $n \times n$ entries. In contrast, *accessibility* is attached to one location and thus refers to an aggregated single-point-value. This corresponds to n entires that would need to be passed.

This chapter provides the theoretical basis of the accessibility measurement. The concept of accessibility, quantitative indicators that can be used in this context, and components of accessibility are discussed in Sec. 6.1.

Section 6.2 looks at the implementation to compute accessibilities at high resolutions. This task is performed in the transport model MATSim. Accessibility measurements in this dissertation will be computed for different travel modes in accessibility computation such as car, bicycle and traveling on foot by using the network oriented performance of the transport system.

The accessibility measurement should ideally be sensitive to (i) changes in the transport system, i.e., the disutility of traveling between an origin and destination location using a specific transport mode, and to (ii) changes on the land use side such as the amount or spatial distribution of opportunities [Geurs and van Wee, 2004, p. 130]. This point is addressed by applying the proposed high resolution accessibility approach to a real-world scenario. In Sec. 6.3, the real-world scenario is described, Sec. 6.4 illustrates the outcomes of this application. In particular, different transport modes, spatial resolutions and resulting computing are presented. This chapter closes with a discussion and a conclusion.

This chapter is an edited version of Nicolai and Nagel [submitted in 2013, 2012a,b].

6.1 ACCESSIBILITY

Persons' choice of their residential location is influenced by how well they can access their activities from there. It is clear that there has to be some influence, however weak since, say, commuting plus working plus sleeping needs to fit into the 24 hours of a day. Similarly, the location choice of firms is influenced by how well they can access their customers from there, or how well suppliers and customers can access them at the location.

In consequence, the suitability of a location for a specific person depends on that person's activity pattern. Similarly, the location for a specific household depends on the activity patterns of all household members, and the location for a specific firm depends on the location of its suppliers and customers. If all these were known, one could compute individual values of every location for persons, households or firms that search for locations.

For many purposes, however, one is interested in a more general value of a given location. For example, a developer might be interested in developing a certain location without knowing the person, household or firm that might eventually occupy it. A family might search for a residence before knowing where for instance the spouse will work. This is where the concept of accessibility comes in: It describes how well a given location can be reached, or how well other locations can be reached from this location.

Researchers assert that accessibility has a measurable impact in the real world [e.g., Vandenbulcke et al., 2009]: Hansen [1959] shows that areas which have more access to opportunities have a greater growth potential in residential development. Moeckel [2006] asserts that the principal idea of Hansen's approach is also true for businesses. In other words: Locations with easier access to other locations are more attractive compared to otherwise similar locations with less access.

Many quantitative indicators can be used for accessibility. Some examples are:

- distance to next shopping area
- travel time [e.g., Vandenbulcke et al., 2009] or distance [e.g., Borzacchiello et al., 2010] to next railway station
- number of opportunities (e.g., workplaces, places to shop) within, say, 1 kilometer.

Comprehensive reviews of accessibility measurements are provided by Geurs and Ritsema van Eck [2001] and Geurs and van Wee [2004].

Accessibility can be seen as the result of the following four independent components [Geurs and Ritsema van Eck, 2001; Geurs and van Wee, 2004]:

1. A **land use** component that deals with the number and spatial distribution of opportunities.
2. A **transport** component which describes the effort to travel from a given origin to a given destination.
3. A **temporal** component which considers the availability of activities at different times of day, e.g., in the morning peak hours.
4. An **individual** component that addresses the different needs and opportunities of different socio-economic groups, e.g., different income groups.

Accordingly, accessibility measures can concentrate on one or several of these components [Geurs and Ritsema van Eck, 2001]:

1. For example, the **infrastructure-based** approach is based on the performance of the transport system. An example would be the average speed by mode at certain locations.

2. The **activity-based** measurement deals with the distribution of possible activity locations in space and time. An example would be the number of shopping locations or workplaces within a certain geodesic distance. Alternatively, one could look at the number of shopping locations or workplaces within a certain travel time, which would combine the infrastructure-based with the activity-based approach.

3. A **utility-based** measurement of accessibility reflects the (economic) benefits, as the maximum expected utility, that someone gains from access to spatially distributed opportunities [Geurs and Ritsema van Eck, 2001; de Jong et al., 2007]. The typical example is the logsum term, also discussed below.

Normally, accessibilities are attached to spatial units i. These spatial units are typically relatively large zones, but one could equally well calculate accessibilities for each parcel or building in the region of interest. In many cases, however, the computational effort for this would be rather large. In addition, it may not be necessary: Since accessibility is a spatially averaged quantity, it is plausible to assume that the accessibility of a building between two other buildings might be interpolated from the two neighboring accessibility values.

Taking this argument further, one could as well consider accessibility as a field, i.e., as continuously varying in space, $A(x, y)$, where x and y are the coordinates. As is common in many areas of science, such fields can be visualized by calculating the values on regular grid points, and then using an averaging plotting routine. A similar approach was also used by [Borzacchiello et al., 2010; Kwan, 1998]. Going beyond [Borzacchiello et al., 2010] the accessibility computation presented in this thesis is not based on Euclidean distance, but using the network oriented performance of the transport system like [Kwan, 1998].

6.2 METHODOLOGY: HIGH RESOLUTION ACCESSIBILITY

6.2.1 *Accessibility indicator*

This section looks at the implementation to compute accessibilities at high resolutions.

In this thesis, a utility-based measurement is selected (e.g., Train [2003]; Ben-Akiva and Lerman [1985]), which is also known as the logsum. It is defined as

$$A_i := \ln \sum_k e^{V_{ik}} , \tag{10}$$

where k goes over all possible destinations, V_{ik} is the disutility of travel in order to get from location i to location k.

The logsum term includes a land use component that considers the number and distribution of opportunities, and a transport component that determines the effort to get there.

It may be useful to recall the origins of Eq. (10). For this, assume that the full utility of location k, seen from i, is $U_{ik} = V_{base} + V_{ik} + \epsilon_{ik}$, where V_{base} is a constant base utility for doing the activity at any location, V_{ik} is the systematic (= observed) disutility to get there, and ϵ_{ik} is a random term which absorbs the randomness of the travel disutility, but more importantly the utility fluctuations of doing the activity around V_{base}. Under the typical assumption that the ϵ_{ik} are independent and identically Gumbel-distributed random variables, the expectation value of U_{ik}, averaged over all possible destinations k, becomes

$$E(U_i) = A_i + Const \ .$$

$Const$ is an integration constant which can, in principle, be computed. It contains both the effect of the base utility, V_{base}, and some constants related to the Gumbel distribution. Since it is the same for all locations, it is typically dropped. As a result, A_i can become negative.

Eq. (10) sometimes includes a so-called scale parameter, which is discussed in Sec. 6.5.

Eq. (10) can be seen as a proxy for other accessibility indicators of the form $g(\sum_k f_{ik})$, where f_{ik} is some measure related to the difficulty of getting from i to k, and g is a typically non-linear and monotonic transformation. For example, with

$$f_{ik} = \begin{cases} 1 & \text{if distance } < 1\,km \\ 0 & else \end{cases}$$

and $g(x) = x$ the indicator counts the number of opportunities within $1\,km$.

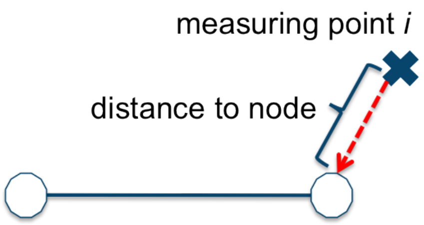
Accessibilities in the present work are computed based on a congested road network with time dependent travel times. As described in Ch. 4, this task is part of the attempt to couple a land use model, UrbanSim [Waddell, 2002; Miller et al., 2005; OPUS User Guide, 2011], with a transport model, MATSim [Balmer et al., 2005a; Raney and Nagel, 2006; Balmer et al., 2009b]. In this configuration, MATSim performs a traffic flow simulation based on the land use and commuting patterns provided by UrbanSim. A comprehensive description of the integration approach of MATSim with UrbanSim is given in Sec. 4.1.

6.2.2 *Overview of computation*

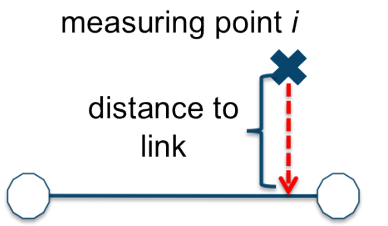
In order to calculate the accessibility A_i, origin locations i and opportunity locations k are assigned to a congested road network with time dependent travel times. For every given origin i, a so-called "least cost path tree" computation runs through the network and determines the best route, and thus the least negative travel utility V_{ik}, to each opportunity location k by using the Dijkstra shortest path algorithm [Dijkstra, 1959]. The best route from i to k depends on the given cost type such as link travel times or distances. Once the least cost path tree has explored all nodes, the resulting disutilities V_{ik} for all opportunities are queried and the accessibility is calculated as stated in Eq. (10).

6.2.3 *Assignment of locations to the network*

Origin and opportunity locations do not necessarily lie on the network as shown in Fig. 31. Thus, the calculation of V_{ik} includes the disutility of travel to overcome the gap between locations and the road network.



(a) Euclidean distance measurement between the origin location i in accessibility calculation and the nearest network node.



(b) Orthogonal distance measurement between the origin i in accessibility calculation and the nearest network link.

Figure 31: The calculation of V_{ik} includes the disutility of travel to overcome the gap between locations such as origins i (blue cross) and the network, which is based on the shortest distance. This is either given by the euclidean distance to the nearest node or the orthogonal distance to the nearest link on the network.

For origin locations i, the shortest distance to the network is either given by (i) the Euclidean distance to the nearest node or (ii) the orthogonal distance to the nearest link on the network. If the mapping of location i is to a link, as in case (ii), V_{ik} further includes the travel disutility to overcome the distance to the nearest node. The travel costs on the link are calculated by dividing the distance to the node by the travel speed of the considered transport mode, e.g., car (free speed or congested car travel times at a given time of day), bicycle or walk. For opportunity locations k, the Euclidean distance to the nearest node is used to determine the shortest distance to the network.

6.2.4 *Disutility of travel*

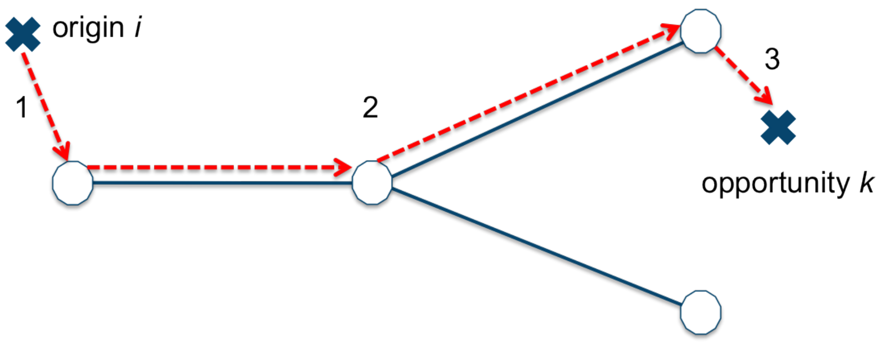


Figure 32: The composition of the travel disutility V_{ik} consists of three parts: (1) The disutility to reach the network from i, (2) the disutility on the network and (3) the disutility to reach opportunity k from the network.

As stated in Eq. (10), the computation of the accessibility for a given origin location i contains a summation of the term $e^{V_{ik}}$ for all opportunity locations k. The determination of the disutility of travel, V_{ik}, consists of the following contributions as depicted in Fig. 32:

1. The disutility of travel of reaching the transport network from origin i, as described in Sec. 6.2.3. It is assumed that opportunities can only be reached via the transport network.

2. The disutility of travel *on* the transport network towards k.
3. The disutility of travel of reaching the opportunity k from the transport network, as explained in Sec. 6.2.3.

As a result, the disutility of travel is composed as follows:

$$V_{ik,tt_{mode}} := \beta_{tt_{wlk}} \cdot tt_{wlk,gap,i} + \beta_{tt_{mode}} \cdot tt_{mode} + \beta_{tt_{wlk}} \cdot tt_{wlk,gap,k} \tag{11}$$

where

- tt_{mode} is the travel time [in h] according to the given transport mode. Transport modes are either car (free speed or congested), bicycle or walk.
- $tt_{wlk,gap,i}$ is the travel time [in h] on foot to overcome the gap between the origin location i and the road network.
- $tt_{wlk,gap,k}$ is the travel time [in h] on foot to overcome the gap between the road network and the opportunity location k.
- $\beta_{tt_{mode}}$ and $\beta_{tt_{wlk}}$ are marginal utilities [in utils/h] that convert travel times into utils. By default, all marginal utilites are set to -12 utils/h. In MATSim terms, this is the sum of the marginal opportunity cost of time (typically -6 utils/h) and the marginal additional disutility of travel (typically another -6 utils/h).

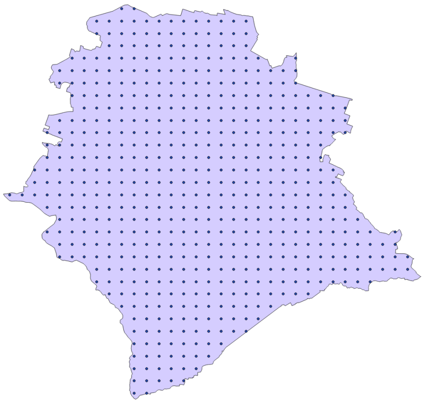
The travel times for traveling by bicycle or on foot are computed by taking the travel distance with a constant velocity of 15km/h (bicycle) or 5km/h (walk).

6.2.5 *Spatial resolution*

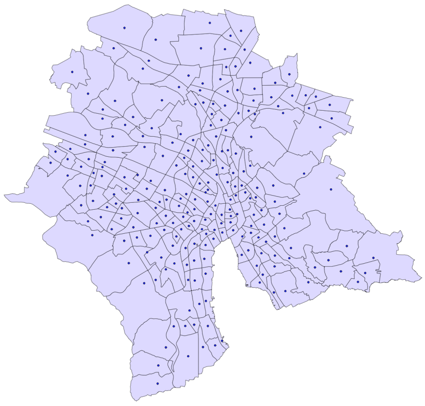
When looking at high-resolution accessibility calculations, there are, in fact, two resolutions to consider: One that defines for how many origins i the accessibility is to be computed. And a second one that defines to what level the opportunities k are to be resolved.

SPATIAL RESOLUTION OF THE ORIGIN In the present implementation, the origin side can be calculated for two spatial units: cells or zones. Their spatial resolution determines the number of measuring points for which the accessibility will be computed:

- **Cell-based Approach**: In this approach the study area is subdivided into square cells, where the resulting cell centroids serve as origins or measuring points for the accessibility calculation, see Fig. 33a. The spatial resolution depends on the selected cell size, which is configurable.
- **Zone-based Approach**: This approach uses zone centroids as measuring points, see Fig. 33b. The centroid coordinates can be obtained from a variety of definitions. In this paper, they are determined by averaging all parcel coordinates that belong to a zone. This corresponds to weighting each parcel equally; this may not be justified when, say, the number of residents or households varies strongly between parcels. This is another example of an assumption that does not have to be made for the high resolution accessibility computation. The number of measuring points is defined by the number of zones.

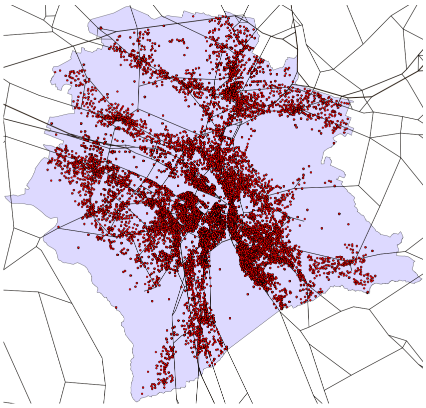


(a) Cell-based approach at the example of $400\,m \times 400\,m$ side length.

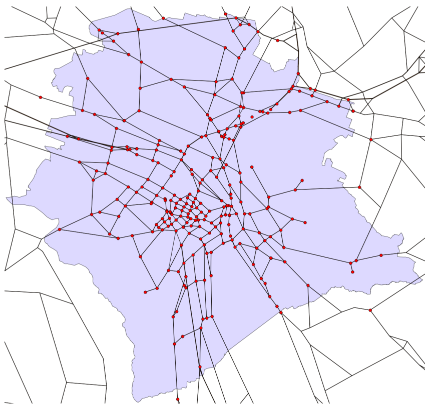


(b) Zone-based approach

Figure 33: The figures visualize the (a) cell- and (b) zone-based approach in accessibility calculation using the example of the city of Zurich (gray area). The origins or measuring points for accessibility calculation are determined as follows: The cell-based approach subdivides the study area in square cells of configurable size; here a side length of $400m \times 400m$ is used for visibility reasons. The cell centroids (blue dots) serve as origins. The zone-based approach is using zone centroids instead which are determined by averaging all parcel coordinates that belong to a zone. The number of measuring points is given by the number of zones.



(a) Opportunities with parcel coordinates (red dots) given by the land use model



(b) Opportunities (red dots), aggregated on the nearest node on the road network

Figure 34: In (a) opportunity locations (dots) provided by the land use model are at a disaggregated parcel level. The spatial resolution inside MATSim depends on the resolution of the road network, i.e., on the number of nodes and link lengths. Thus, opportunities are directly aggregated to their nearest node on the given road network as depicted in (b).

In both cases, the accessibility computation is valid for the measuring point. In the grid-based approach, MATSim uses the measuring points to obtain accessibilities for each UrbanSim parcel. This is done by interpolating the accessibility from the grid-cell. In contrast, for the zone-based approach the accessibility of the measuring point is taken as representative for the whole zone. In consequence, the choice of the procedure of how to generate the measuring point for the zone-based approach has an influence on the results. There is no corresponding choice for the grid-based approach, removing one element of arbitrariness compared to the zone-based approach.

The following paragraphs concentrate on the cell-based approach that is qualified for high resolution accessibility calculations. Nevertheless, the calculation procedure of the logsum term is the same for both approaches.

SPATIAL RESOLUTION OF OPPORTUNITIES Opportunity locations such as work places are given by land use. Unlike origins, for the present paper such locations are directly aggregated to the nearest node on the road network as depicted in Fig. 34.

6.2.6 *Computational procedures*

Exploring the entire network by using the "least cost path tree" is a computationally expensive task. In order to accelerate the overall computing speed, the execution time of the "least cost path tree" is reduced by the following elements.

ORIGINS For each origin location i, the nearest node on the road network is identified. Locations that share the same node have the same travel disutilities on the network. In this case, the "least cost path tree" is executed only once, and the calculated disutilities on the network are reused for all i that are mapped on the same node. Only the calculation of the travel disutility to overcome the gap between location i and the network is done individually.

OPPORTUNITIES It is, in fact, sufficient to sum over all opportunities k attached to a node j only once. For this, assume that the travel disutility V_{ik} can be decomposed as

$$V_{ik} = V_{ij} + V_{jk} \; \forall k \in j \;,$$

where the notation $k \in j$ shall refer to all opportunities k attached to node j. Then

$$\sum_{k \in j} e^{V_{ik}} = \sum_{k \in j} e^{(V_{ij} + V_{jk})} = \sum_{k \in j} e^{V_{ij}} e^{V_{jk}}$$

$$= e^{V_{ij}} \sum_{k \in j} e^{V_{jk}} =: e^{V_{ij}} \cdot \mathrm{Opp}_j$$

Thus, it is sufficient to compute Opp_j once for every network node j, and from then on compute accessibilities by

$$A_i = \ln \sum_k e^{V_{ik}} = \ln \sum_j e^{V_{ij}} \cdot \mathrm{Opp}_j \;.$$

This is an exact result. The only approximation was already done earlier; it is that all opportunities are matched to only one network node.

6.3 SCENARIO

The above approach is applied to a real-world scenario, the city of Zurich, a parcel-based UrbanSim application. A comprehensive description about the Zurich application is given by [Schirmer et al., 2011; Schirmer, 2010]. At this point, a brief overview is provided.

The Zurich case study uses the year 2000 as the UrbanSim base year. It stores the initial state of the study area. The data that is needed to create the base year such as a population census, mobility census, enterprise census, etc., comes from several sources that can be divided into two main categories: governmental and private data. The sources for governmental data include various Swiss federal, cantonal,[1] and municipal offices. The acquisition of private data includes private institutions, websites and self created data.

The Zurich application consists of 40'407 parcels, 234 zones, 336'291 inhabitants and 316'703 jobs. In the following, the UrbanSim base year, 2000, is used to create the input for the MATSim runs. After that, UrbanSim is no longer needed for the present setting.

6.3.1 *Population and initial demand*

In order to speed up computation times, MATSim considers a 10% random sample of the synthetic UrbanSim population consisting of 33'629 agents. All MATSim agents have complete day plans with "home-work-home" activity chains. Work activities can be started between 7 and 9 o'clock and have a typical duration of 8 hours. The home activity has a typical duration of 12 hours and no temporal restriction.

6.3.2 *Network and adjustments*

A revised Swiss regional planning network [Vrtic et al., 2003; Chen et al., 2008] is used including major European transit corridors as shown in Fig. 35. The network consists of 24'180 nodes and 60'492 links, where each link is defined by an origin and a destination node, a length, a free speed car travel time, a flow capacity and a number of lanes. In addition, each link obtains congested car travel times once the traffic flow simulation in MATSim is completed as described in Sec. 3.7.

The following summarizes modifications to improve link capacities especially at the urban scale based on [Grether et al., 2008; Chen et al., 2008]. All links within a radius of 4 kilometers around the Zurich city center were modified as follows:

- Links that correspond to so-called primary[2] roads in OpenStreetMap[3] (OSM) get a capacity of at least 2000 vehicles per hour. Links with higher capacities remain unchanged.
- Links that correspond to secondary roads in OSM keep their initial capacity (usually between 1000 and 2000 vehicles per hour).
- The remaining links get a capacity with a maximum of 600 vehicles per hour. If the original capacity is lower, it is not changed.
- Finally, a few individual links are adjusted manually based on local knowledge.

The flow and storage capacities of the road network are automatically adjusted based on the given population sampling rate used for the MATSim

1 A Swiss Canton corresponds to a federal state
2 an Open Street Map road classification is given at `http://wiki.openstreetmap.org/wiki/Highway_tag_usage`
3 see `http://www.openstreetmap.org`

runs. This is done in order to preserve congestion effects when running MATSim at small samples. The flow capacity gives the maximum number of vehicles per time unit that can pass a link [Nagel, 2007]. It is adjusted by a flow capacity factor which is set to the same value as the given Population Sampling Rate. The storage capacity defines the maximum number of vehicles that can be on a link [Nagel, 2007]. The corresponding storage capacity factor is defined as

$$\text{Population Sampling Rate}/\text{Heuristic Factor}\,, \tag{12}$$

where the Heuristic Factor $=$ (Population Sampling Rate)$^{-1/4}$. The Heuristic Factor aims to raise the storage capacity especially at low sampling rates to avoid network breakdowns caused by strong but spurious backlogs. This effect is explained by Rieser and Nagel [2008].

Figure 35: The Zurich case study network, area of Zurich (blue) enlarged.

6.3.3 *Traffic simulation*

A MATSim run is performed by running the simulation for 1000 iterations. During the first 800 iterations, 10% of the agents perform "time adaptation" which changes the departure times of an agent and 10% adapt their routes. The remaining agents switch between their plans. During the last 200 iterations, time and route adaptations are switched off; thus, agents only switch between existing plans.

6.4 ILLUSTRATIONS

This section illustrates the outcomes of the proposed high resolution accessibility approach using the example of work place accessibility. In the following, accessibility measures are applied to the MATSim run mentioned in Sec. 6.3.3. In particular, the influence of the spatial resolution on the quality of the results and on computational performance are considered. Moreover, different travel modes in accessibility computation are compared, which are congested and free speed car, bicycle and walk. In Appendix B.1, an additional sensitivity test is presented to investigate the impact from changes on the road network on the accessibility outcome.

All measurements are applied for the morning peak hour at 8am. At this time most travelers are commuting to work. Tab. 7 summarizes relevant parameter settings.

	Default Setting
Resolution	$100m \times 100m$
Travel Cost	congested car travel times [minutes]
$\beta_{tt_{car}}$	-12utils/hour
$\beta_{tt_{wlk}}$	-12utils/hour

Table 7: Default settings for the accessibility computation.

6.4.1 *Default setting*

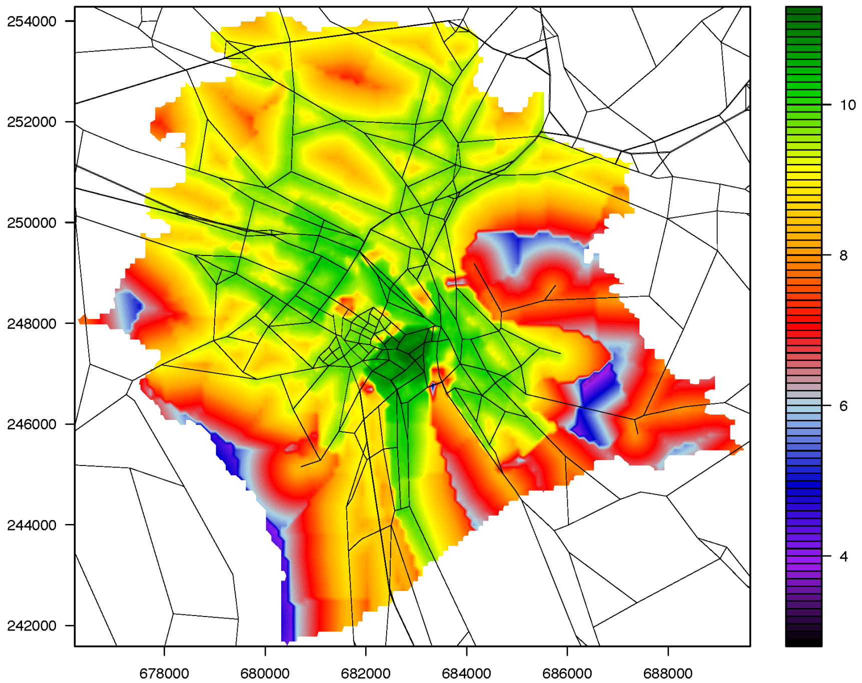
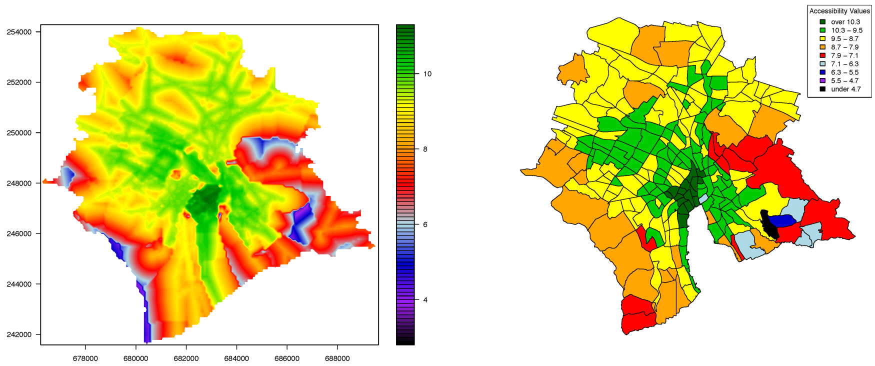


Figure 36: This depicts the outcome of the proposed accessibility measurement using the "Default Settings" as stated in Tab. 7. To improve interpretability, the road network is overlayed.

Figure 36 depicts the accessibility outcome using the "Default Setting" as stated in Tab. 7. To improve interpretability, the road network is overlayed. The colored scale bar on the right hand side indicates the accessibility level, where a good work place accessibility is indicated by green areas and poor accessibility is indicated by dark blue or black areas.

The plot exhibits very good work place accessibility in areas that provide a high density of opportunities and a well developed road network. These characteristics apply for the inner city, where the highest utility values are measured, and the areas along the major access roads from and to Zurich, visible as green or yellow corridors. In contrast, areas with less workplace accessibility have a gradient from red to dark blue or black. This for instance applies for the "Zürichberg" and the "Uetliberg" which are two undeveloped wooden hills located in the east and south west part of Zurich. The several "islands of low accessibility" in the center of Zurich are due to localized congestion on those links: If there is strong congestion at the origin, then *all* opportunities k incur a strongly negative V_{ik} and thus make only a small contribution to the sum.



(a) The same as Fig. 36, but without showing the road network.

(b) The same congestion data as Fig. 36, but now based on zones as is traditionally done.

Figure 37: Alternative representations of the same congestion data as Fig. 36.

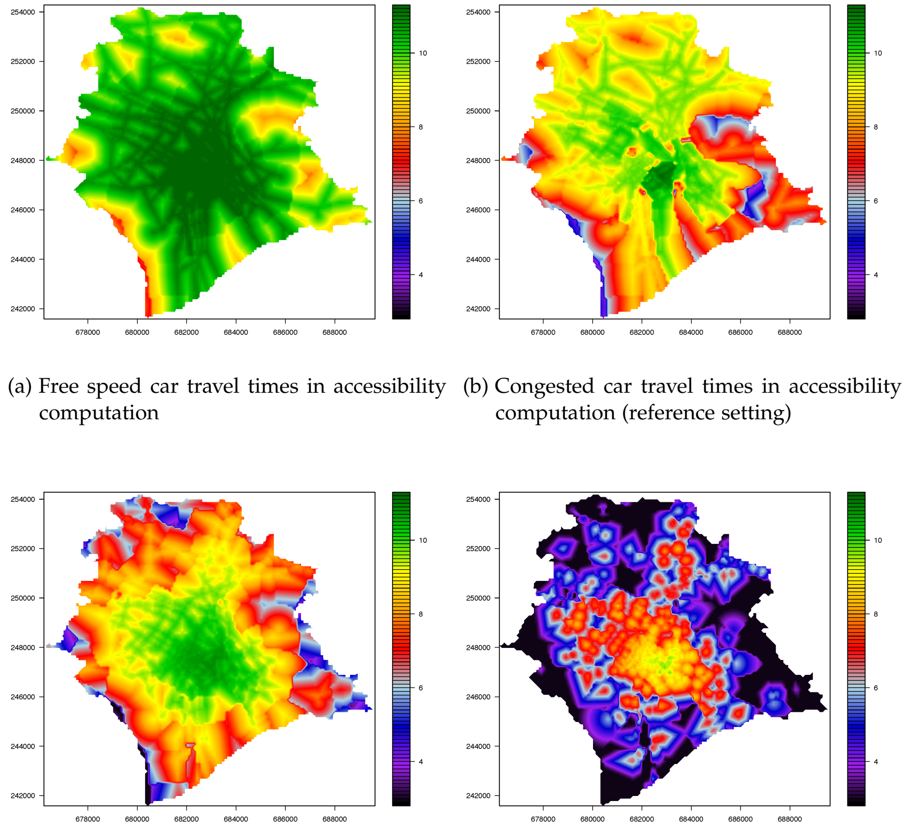
It should be noted that accessibility is now smooth in space, see Fig. 37. Figure 37a is the same as Fig. 36, but without the road network. One clearly sees how highly accessible areas trace the road network. The zone representation of the same data is shown in Fig. 37b. Clearly, all additional spatial resolution within the zones is now gone. Also, with the zones approach the question in how far the transport network becomes visible in the accessibility plot hinges entirely on the question if the zones reflect the structure of the transport network or not. Such arbitrariness is removed with an approach that does not rely on zones.

6.4.2 *Mode*

At this point, different travel modes in accessibility computation are compared. These are car, bicycle and walk. For car, free speed and congested travel times are used. The travel times for traveling by bicycle or on foot are computed by taking the travel distance with a constant velocity of 15km/h (bicycle) or 5km/h (walk).

The outcomes are shown in Fig. 38. The first two plots are illustrating how congestion significantly reduces accessibility. The third and fourth plot illustrate accessibility by bicycle and by walking, respectively. Congestion has no effect on these modes. Both plots show that spatial proximity to opportunities has a strong influence on the results. Locations away from the city center and the commercial areas in the northeast and western part of Zurich have a rapidly decreasing accessibility. As seems plausible, near the city center the bicycle provides similar accessibility as the car under congested conditions. Farther away from the center, the car gains ground even under congested conditions.

Overall, one might speculate that Fig. 38a is what people who plan to use a car expect, but Fig. 38b is what they actually get. And what they actually



(a) Free speed car travel times in accessibility computation

(b) Congested car travel times in accessibility computation (reference setting)

(c) Bicycle travel times in accessibility computation

(d) Walk travel times in accessibility computation

Figure 38: These plots visualize the influence of different transport modes on the accessibility computation.

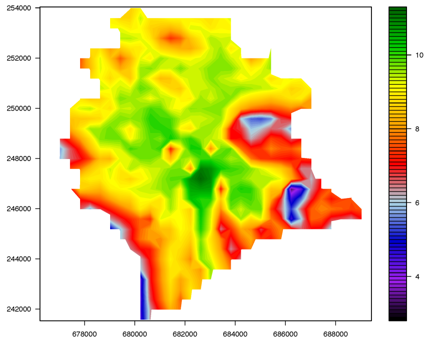
get is not much different from what one gets by using a bicycle (Fig. 38c). In contrast, walk is truly much worse (Fig. 38d).

6.4.3 *Spatial resolution*

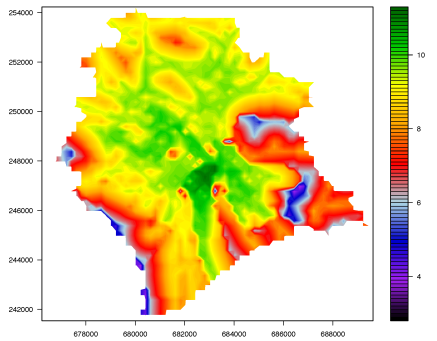
Figure 39 shows the outcome of the accessibility measurement at the following resolutions: $50\text{m} \times 50\text{m}$, $100\text{m} \times 100\text{m}$, $200\text{m} \times 200\text{m}$ and $400\text{m} \times 400\text{m}$. In terms of information gain it can be stated that the lowest resolution with $400\text{m} \times 400\text{m}$ provides a rather undifferentiated picture, whereas higher resolutions lead to more detailed measurements. In the $50\text{m} \times 50\text{m}$ resolution, even fine road structures in the city center are clearly visible. However, a significant increase in the level of detail can be observed up to the resolution of $100\text{m} \times 100\text{m}$. The higher resolution ($50\text{m} \times 50\text{m}$) looks smoother and sharper, but does not offer noticeable gains.

6.4.4 *Computing times*

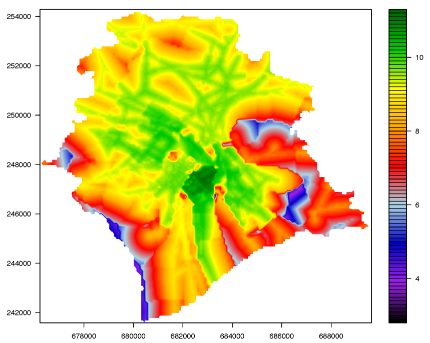
In Sec. 6.4.3, the resolution of two successive plots is doubled. This corresponds to a quadrupling of the measuring points. However, this increase is not reflected in the computing times, see Tab. 8, due to the run time op-



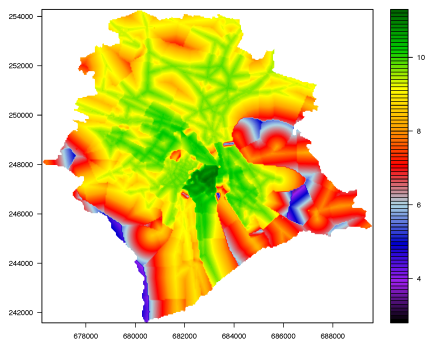
(a) Resolution $400\text{m} \times 400\text{m}$



(b) Resolution $200\text{m} \times 200\text{m}$



(c) Resolution $100\text{m} \times 100\text{m}$



(d) Resolution $50\text{m} \times 50\text{m}$

Figure 39: Results of different resolutions. In ascending order from the top left to the bottom with the following cell sizes $400\text{m} \times 400\text{m}$, $200\text{m} \times 200\text{m}$, $100\text{m} \times 100\text{m}$ and $50\text{m} \times 50\text{m}$.

Cell Resolution	**Origins**	**Aggregated Opportunities**	**Computing Time [min]**
$50\text{m} \times 50\text{m}$	36 748	272	2-3
$100\text{m} \times 100\text{m}$	9195	272	2
$200\text{m} \times 200\text{m}$	2292	272	≈ 2
$400\text{m} \times 400\text{m}$	577	272	≈ 1
Zone Resolution	**Origins**	**Aggregated Opportunities**	**Computing Time [min]**
Given by zones	234	272	≈ 1

Table 8: This table lists the computation times to measure accessibility at different resolutions and the zone level. All measurements are performed on a Mac Book Pro with an Intel Core 2 Duo 2.5 GHz processor and 4 GB of memory. Currently 1 CPU core is used to execute the accessibility computations.

timizations outlined in Sec. 6.2.6. Instead, there is no advantage in terms of computing speed for the traditional zone based accessibility measure despite the low resolution.

6.5 DISCUSSION

THE UNIT OF THE ACCESSIBILITY MEASUREMENT The logsum term, Eq. (10), sometimes contains a scale parameter, i.e., it reads

$$(1/\mu) \ln \sum_k \exp(\mu \tilde{V}_{ik}). \tag{13}$$

When the utility function is estimated, Eq. (10) is the correct form [also see Train, 2003]. Clearly, the user can decompose the estimated utility function V_{ik} as $V_{ik} = \mu \tilde{V}_{ik}$, in which case Eq. (10) needs to be replaced by Eq. (13) in order to obtain the accessibility in the rescaled units. This may, for example, be useful if the utility function is to be scaled to monetary units, and accessibility is to be expressed in those same monetary units. Since $\mu\tilde{V}_{ik}$ is the same as V_{ik}, such re-scaling does not change the structure of the plots; however, all accessibility values will be multiplied by $1/\mu$.

SPATIAL RESOLUTION In this chapter, most plots are based on a grid resolution of $100m \times 100m$ and the road network as shown in Fig. 35 and 36. As it was argued, higher spatial resolutions with the same road network do not lead to discernible improvements. In contrast, a higher resolution road network would clearly make a difference. The present method assumes that the access from an arbitrary location to the nearest network element (node or link) is done by walking. However, there are additional roads beyond those that are used for the computation and thus it is quite plausible that – both for car and bicycle – access to the network is much faster than assumed in the plots. This issue is reduced when using a higher resolution network since any kind of approximation about how to reach the transport network will then have a smaller impact.

Using a higher resolution road network is feasible – the computational cost scales roughly in the number of links since the worst case complexity of the Dijkstra tree computation is roughly linear in the number of links for planar graphs. In the present situation, it was decided to keep the lower resolution network. One reason was to investigate how the proposed approach would perform in such a situation. Another reason was that there was no higher resolution network together with a calibrated scenario available.

COMPUTING TIMES Computing times could be further improved by using multiple threads: Since the computations for different origins are independent, they could be distributed between all available CPU cores.

6.6 CONCLUSION

Accessibility measures are, for a given origin, a weighted sum over possible destinations. In this thesis, the econometric logsum term is used as an example. It measures accessibility as a benefit that someone at a specific location derives from access to spatially distributed opportunities. It includes, as usual, a land use component by considering the distribution of opportunities and a transport component by determining the effort to get there.

The present chapter applies this approach to a real-world scenario – the city of Zurich (Switzerland) – with the example of measuring work place accessibilities. The measure is tested for (i) different resolutions and (ii) several transport modes such as car, bicycle and traveling on foot. In addition,

(iii) a sensitivity test was carried out in the Appendix B.1, where the Schöneichtunnel, an important access road, is closed.

Important results include:

- The approach is able to provide a spatially differentiated picture. Artifacts such as supposedly homogeneous accessibility within zones are removed.
- The computation of a cell-based accessibility measurement at high resolutions is computationally feasible.
- For the present scenario and network, a resolution finer than $100\mathrm{m} \times 100\mathrm{m}$ does not deliver noticeable additional gains. The reason for this is the spatial resolution inside MATSim which is determined by the road network. It is given by the (i) number of nodes that incorporate opportunities and (ii) the broad range of different link lengths which are in this configuration at least 200 meters long for the inner city of Zurich. There is no additional resolution beyond the network. The present network is created for Swiss-wide planning purposes and thus has a limited resolution.
- The effect of congestion is very clearly visible. The result also confirms that, in the urban core, accessibility by bicycle is similar to accessibility by car during congested peak hours. Outside the urban core, however, accessibility by bicycle is clearly worse than by car also during peak hours.

  In contrast, accessibility when walking is definitely much worse than either by car or by bicycle and reaches levels comparable to accessibilities by bicycle or by car only in the inner center of the city.
- Currently, one CPU core is used to perform the accessibility computations. Given that these are independent calculations, computing times can be accelerated by parallelization. Then computing times can be divided by the number of available CPU cores.

7 CONCLUSION AND OUTLOOK

This chapter provides a brief summary about the main stations of this work and explains the main features of the MATSim for UrbanSim integration (Sec. 7.1). Also the challenges of this topic are addressed. The chapter concludes with an outlook showing possible developments and extensions for the near future (Sec. 7.2).

7.1 SUMMARY

Land use and transport interaction (LUTI) models allow to perform comprehensive impact analysis and evaluation of public policies such as congestion pricing or public transport. They provide a comprehensive tool to help planners and decision makers in government assessing the impact of infrastructure measures and to improve policy and investment decisions.

LUTI models can be seen as simplifications of the urban system. Wegener [2004] identified nine subsystems modeling the urban change processes which evolve with different speeds.

LUTI models combine land use and transport models with feedback mechanisms between them. Their 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. Accessibility provided by transport influences location decisions of socio-economic actors such as households, firms and developers. On the other way, land use consisting of the number and spatial distribution of activity locations like work, shopping or leisure, determines the need for spatial interaction [Wegener, 2004; Strauch et al., 2005; Wegener, 2011; Geurs and Ritsema van Eck, 2001].

An integrated view of the interactions between land use and transport is crucial to understand and forecast effects of modifications to the urban system [Borzacchiello et al., 2010; Wagner and Wegener, 2007], e.g., modifications on the structure of the transport system, the land use patterns and the environment.

Accessibility is a central measurement. Generally, it is a measurement of attractiveness. The important aspect in the context of LUTI models is that accessibility measures how opportunities, e.g., workplaces, locations for shopping and leisure activities, are linked with each other via the transport network. In other words, it describes how well a given location can be reached, or how well other locations can be reached from this location. An extensive review of accessibility indicators by [Geurs and Ritsema van Eck, 2001; Geurs and van Wee, 2004] identifies four different components in accessibility indicators: (i) land use, dealing with number and spatial distribution of opportunities, (ii) transport, describing the effort of traveling, (iii) temporal, considering the availability of activities at different times-of-day and (iv) individual, addressing the needs and opportunities of different socio-economic groups. Geurs and Ritsema van Eck [2001] further identify three perspectives on measuring accessibility: (i) infrastructure-based, (ii) activity-based and (iii) utility-based accessibility.

So far, operational state-of-the-art models taking the interaction between land use and transport into account are still missing or are not implemented in a consistent way. One example is the integration of UrbanSim, a microscopic land use model, with traditional transport models that do not make use of the disaggregated nature and individual detail provided by the land use model.

This dissertation aims to address this issue as part of the SustainCity project [SustainCity Work Description, 2010; SustainCity www pages, accessed February 2012], founded by the European Union Seventh Framework Programme (FP7). The goal of the project is to improve urban simulation tools and to facilitate the application of such tools among planners and decision makers in government as decision aids for sustainable developments in the European context. The project addresses both modeling and computational issues of coupling the latest micro-simulation models of land use and transport. SustainCity builds on the open source platforms OPUS/UrbanSim (Open Platform for Urban Simulation) and MATSim (Multi-Agent Transport Simulation) which are both distributed under the GNU Public License (GPL). The main challenges on the modeling side are to develop and add additional modules such as a demographic and environmental module in order to adapt UrbanSim, originally developed for cities and metropolitan areas in the United States, to the European context.

UrbanSim provides a shared open source modeling platform that allows cumulative scientific contributions, i.e., UrbanSim offers the opportunity to add new modules or to improve and adapt existing modules as mentioned above. MATSim is a disaggregated, agent-based transport model that is designed to simulate several million agents individually for large real-world transport scenarios.

This dissertation introduced concepts and implementation details to couple the agent-based microsimulation models UrbanSim with MATSim. The integrated modeling framework is also referred to as MATSim4UrbanSim. The integration was developed by taking the robustness of the software integration and the configurability and usability of the integrated modeling framework into account. Also, the computing times of traffic simulation are addressed by the so-called warm and hot start capability. To utilize the agent-based modeling technique, both models were linked directly at a person-centric level, i.e., agents can be transferred and clearly identified among both frameworks.

One objective of the integration was to provide better travel model results, based on realistic network-oriented travel times including congestion effects, into UrbanSim. This work supplemented the MATSim analysis capability by high resolution accessibility computations.

The travel model takes the land use information and population from UrbanSim, simulates their joint travel and computes the output. This includes zone-to-zone impedances, individual agent-based performances and accessibility indicators. The results from the travel model are fed back into UrbanSim, where they are taken into account in several sub-models reflecting the decisions of socio-economic actors such as households, firms, and developers.

Both, the integration of MATSim with UrbanSim as well as the accessibility computation were analyzed. A large-scale real-world scenario for the Puget Sound region, state of Washington (USA), showed the applicability of the integrated modeling framework. Another real-world scenario, the city of Zurich (Switzerland), illustrated the outcomes of the accessibility calculation. Important results include that accessibility now varies smoothly in space; artifacts such as homogeneous accessibility within zones are removed. Furthermore, the computation accessibility measurements at high resolutions is computationally feasible.

The main challenges to be solved include:

1. To achieve a robust coupling between UrbanSim and MATSim.
2. To address the large amounts of computing times that travel models typically need to perform the traffic simulation.
3. To find a way to feedback the microscopic information from the travel model to UrbanSim.

An additional challenge was to apply the travel model for differed spatial resolutions that are supported by UrbanSim such as parcels and zones.

As described in the previous chapters, the following steps were undertaken and implemented:

The first challenge was addressed by providing a joint configuration for both simulation frameworks and to introduce a "certified grammar". The UrbanSim side was selected as the place to manage the joint configuration since it embeds MATSim as a travel model plug-in. To run the travel model, UrbanSim generates the MATSim configuration by using a "certified grammar" that allows to validate the configuration. Moreover, it ensures that modifications of the exchange syntax are always changed consistently on both ends.

The next challenge was addressed by the so-called warm and hot start capability. Both approaches are based on the reuse of information, e.g., travel schedules including route and departure time decisions of agents from a previous MATSim run.

In order to address the last item, the microscopic analysis capability inside MATSim was extended to provide accessibility indicators as feedback to UrbanSim. The proposed approach is capable to measure accessibilities at high resolutions. Normally, accessibilities are attached to spatial units like zones. The outcome of the high resolution accessibility approach provides a spatially differentiated picture. Artifacts such as supposedly homogeneous accessibility within zones are removed. In this thesis, a utility-based measurement was selected that is also known as the logsum [e.g., Train, 2003; Ben-Akiva and Lerman, 1985], which can be seen as a proxy for other accessibility indicators. It measures accessibility as a benefit that someone at a specific location derives from access to spatially distributed opportunities [Geurs and Ritsema van Eck, 2001; de Jong et al., 2007]. The present accessibility measurement was tested for different resolutions and several transport modes such as congested and free speed car, bicycle and traveling on foot.

As mentioned above, the MATSim feedback also includes zone-to-zone impedances comprising travel times for several transport modes, travel distances, generalized travel costs and vehicle trips for each pair of zones as well as individual agent-based performances such as the selected transport mode and the travel times and distances for both directions, commuting from home to work and back.

As part of this dissertation, a public transport (PT) module (the "improved pseudo pt") was implemented that uses information about public transport stops in order to produce so-called teleported public transport legs. This means that agents traveling by public transport are not executed on the physical road network but instead these agents are teleported from one location to the next. The travel time and distance are calculated based on the given public transport stops. Alternatively, stop-to-stop travel times and distances can be specified. This approach gets in line between the existing public transit schedule [Rieser and Nagel, 2009; Rieser, 2010] and the pseudo pt [Grether et al., 2009; Rieser and Nagel, 2009].

In order to simulate different toll schemes such as distance, cordon or area toll, the existing MATSim road pricing module [Kickhöfer et al., 2010; Nagel et al., 2008; Rieser et al., 2008; Grether et al., 2008; Beuck et al., 2006] was plugged in and became a permanent feature within the MATSim with UrbanSim integration.

This development provides a comprehensive tool to analyze and evaluate transport and land use related policies. It is currently being used for two case studies for the canton of Zurich (Switzerland) and the metropolitan region of Brussels (Belgium). The present work hopefully fosters usage of integrated urban simulation models for further case studies as well as the prospective design of sustainable urban planning measures.

7.2 OUTLOOK

During the development of MATSim4UrbanSim, and later when it was used for the first case studies, new ideas and suggestions emerged from colleges and project partners for further improvements or extensions, which were not the focus of this dissertation. At this point, these ideas and suggestions are briefly discussed:

OUTSOURCING FEATURES OF MATSIM4URBANSIM For the MATSim with UrbanSim integration MATSim has been expanded continuously by new features. Two prominent examples are the improved pseudo pt to simulate public transport and the high resolution accessibility analysis. These features are currently an inherent part of MATSim4UrbanSim. However, it would be desirable to use their functionality independently from MATSim4UrbanSim.

Thus, it is planned for the near future to outsource these features as separate modules, so-called "contribs". Such contribs can be flexibly integrated into MATSim projects if needed and, thus, they can be used by a broader research community.

ADDING ACCESSIBILITY BY PURPOSE The proposed high resolution accessibility analysis inside MATSim is capable to measure accessibilities at different resolutions and for different transport modes. The current approach is implemented using the example of work place accessibility.

However, the accessibility computation could be extended by a broad range of activity or opportunities locations. For instance, households are probably interested in the accessibility of schools, leisure and shopping facilities. Accessibility to sales markets and suppliers are taken into account by firms.

COMPUTATIONAL IMPROVEMENTS Currently, accessibility computations are performed by using one CPU core. Given that accessibility measurements for each location are independent calculations, computing times could be reduced by distributing these calculations over available CPU cores.

ADDING ADDITIONAL TRIP PURPOSES BESIDES "HOME" AND "WORK" Currently, MATSim4UrbanSim simulates home-work-home commuting trips based on the available information in the UrbanSim persons data set.

Nevertheless, also non-work traffic flows such as traveling to school, leisure or other activities than work should be added.

ADDING MORE REALISTIC PUBLIC TRANSPORT The current integration approach is using the improved pseudo pt to simulate public transport.

In future projects, the MATSim "public transit schedule" could be considered for this purpose. As mentioned earlier, it is capable to simulate the public transport service in very high detail by using information about public transit lines, their routes, the travel time between stops and the time of departure at the start of the route. However, for the present project the data availability was a problem.

Part I

APPENDIX

A SOFTWARE DESIGN ISSUES

This chapter proposes methods, concepts and software design decisions to integrate UrbanSim and MATSim. Both modeling frameworks are implemented in different programming languages – UrbanSim uses Python, MATSim is implemented in Java. A major challenge includes to achieve a robust software integration between UrbanSim and MATSim. In this sense, also one joint configuration for the integrated software is considered and introduced. Normally, both simulation frameworks come with their own configuration file. However, configuring both frameworks separately would turn into a complicated and error-prone task and result in fragile configurations that are inconvenient to maintain by users. Another challenge is to deal with different spatial resolutions such as zones and parcels.

The chapter is organized as follows. The next section introduces a previous prototype approach that couples both simulation models. In A.2, pitfalls of the integration process and new methods and concepts are presented. Two main concepts to integrate the modeling frameworks are identified and analyzed in A.3 and A.4. It also includes the description of the new joint configuration. The proposed methods and concepts are discussed in the following section. Finally, A.6 summarizes the results and concludes.

This text can be found in similar form in Nicolai and Nagel [2010].

A.1 A PREVIOUS PROTOTYPE

This section aims at describing a previous prototype approach integrating MATSim into UrbanSim and its drawbacks [Nagel, 2008]. A detailed description of both UrbanSim and MATSim is given in Sec. 2.6 and Ch. 3 respectively.

At this point, a brief overview of the prototype integration approach and the interaction between UrbanSim and MATSim is given. The following steps are executed iteratively for each UrbanSim simulation year:

1. **UrbanSim initialization**: For each simulation year (=iteration), UrbanSim needs the initial state of the study area for that particular year in order to simulate the evolution of the urban system. Either the required data sets are obtained from a given base year – this is the case for the initial UrbanSim iteration – or from the previous iteration. The data sets for instance incorporate individual persons, households, buildings and jobs and their relations among each other. Further, the distribution of activity locations, e.g., residence and work location, are defined.

2. **Demand generation**: UrbanSim constructs the input for the travel model and calls it. The input consists of two input files including the distribution of persons and their workplaces on a parcel level. Additional resources such as the traffic network are provided via a *separate* MATSim configuration file.

3. **MATSim run**: MATSim takes the input, generates the traffic assignment and computes the zone to zone impedance matrix including zone to zone travel times as feedback for UrbanSim. Once the travel model

has terminated, UrbanSim takes back control, reads the travel model output and updates its data sets for the following year (= iteration).

4. **Next UrbanSim iteration**: Resume with step 1, otherwise shutdown.

The prototype approach uses a file-based communication between UrbanSim and MATSim through generating the travel demand stored as files for MATSim and importing the resulting zone-to-zone impedances in UrbanSim. Besides, both frameworks have their own configuration file with a different format. These configuration files need to be readjusted separately in order to run different scenarios or case studies. Moreover, both configuration files contain hard coded references. Hence, the following drawbacks of this prototype approach can be stated:

1. **Hard coded**: Hard coded parts like the in- or output file locations and a fixed set of indicators to be calculated by the travel model makes it impossible for users to adapt settings for their own needs without programming expertise in Java and / or Python. This results in an inconvenient and inflexible setup of both frameworks in order to run them correctly on different computers and to use them for various case studies.

2. **Separate configuration files**: Maintaining or adapting two separate configurations at different locations leads to an inconvenient and error-prone setup to run both frameworks with a meaningful and correct configuration.

3. **Extensibility**: Finally, it is difficult to add new functionality to improve this integration approach.

These drawbacks are addressed in the following section with the objective to find an alternative, more robust and flexible approach coupling UrbanSim and MATSim.

A.2 INTRODUCING NEW METHODS AND CONCEPTS TO INTEGRATE URBANSIM WITH MATSIM

As mentioned in Sec. A.1, the fragility of the current software integration is caused by the inconvenient handling of separate configuration files, distributed on different locations, and hard coded references in both simulation frameworks, e.g., to input and output files. This easily leads to inconsistent and error-prone configurations that are inconvenient to maintain by users.

To address these issues, an integral part of the integration is to provide a joint configuration for both frameworks. For this purpose, the UrbanSim side is selected as the place to manage the joint configuration since it embeds MATSim as a travel model plug-in. The joint configuration is achieved by embedding necessary MATSim parameters into the travel model configuration section of the UrbanSim configuration as shown in Fig. 40. With this approach, both simulation frameworks are conveniently configurable via the OPUS GUI (Graphical User Interface). Moreover, this enables the UrbanSim process structure to trigger the travel model and to use MATSim as a travel model plug-in. Necessary MATSim parameters for example include, for instance, the reference to the road network, the number of MATSim iterations, the population sampling rate to accelerate computation times and many more. Detailed travel model configurations, e.g., to configure toll charges and other MATSim features, should be made within the standard MATSim configuration file.

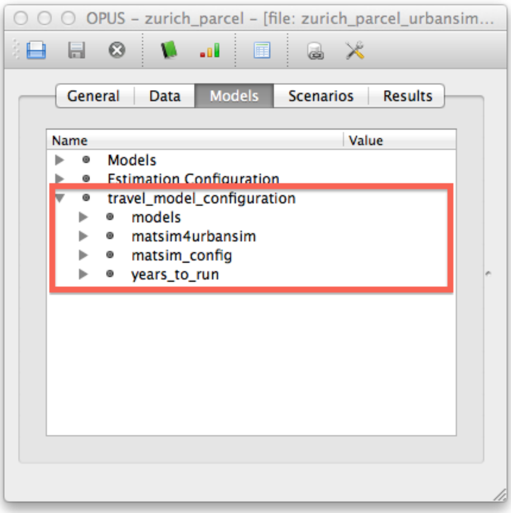


Figure 40: Relevant MATSim parameters are configurable via the OPUS GUI. They are embedded in the travel_model_configuration section (marked in red) as part of the UrbanSim configuration.

In this set-up, UrbanSim needs to pass the settings from the travel model section to MATSim. There are several ways to realize that. Two main concepts can be identified:

1. **File-based coupling**: In this approach, UrbanSim generates a MATSim configuration file. In order to achieve a robust and reliable file-based communication the configuration follows a predetermined specification and can be validated, e.g., in MATSim, against this. The validation incorporates a syntax and parameter type (string, int, float) check. A detailed explanation is given below in Sec. A.3. The input data generation remains file-based like the current prototype approach.
2. **Object-based coupling**: It is desirable to communicate directly and bi-directionally between UrbanSim and MATSim. This means to exchange data via the main memory and to access and execute MATSim classes and methods directly by UrbanSim such as other ordinary UrbanSim packages. Sec. A.4 gives an idea an object-based communication can be applied.

The following sections describe both approaches in detail.

A.3 FILE-BASED COUPLING VIA DATA BINDING

In this section, it is assumed to have a centralized joint configuration. In order to configure and run MATSim properly, UrbanSim extracts the parameter from the transport model section and generates a configuration in Extensible Markup Language format. XML is an acronym for Extensible Markup Language [XML www page, accessed 2013].

Technically, it is not very difficult to use Application Programming Interfaces (API) like the Simple API for XML (SAX) and the Document Object

Model (DOM) in UrbanSim and MATSim to generate and process XML documents. However, it is error-prone and costly to build and maintain such extensions, especially when parameters or the configuration structure change. This considerations lead to two main requirements for a centralized configuration:

1. A mutual consent between UrbanSim and MATSim regarding the structure of the configuration file is crucial. In other words, a validation of the XML is essential, e.g., see Fig. 41.

2. In case of changes regarding the structure of the configuration, e.g., when a new parameter is added, the XML processing modules and classes in UrbanSim and MATSim needed to be adapted automatically.

The so-called XML data binding fulfils both requirements. It is a technique to link different applications by transforming XML documents into an object of the desired programming language. Basically, this allows the transformation of a Python-object in UrbanSim into a Java-object in MATSim via XML. This is similar to pass a configuration-object from UrbanSim to MATSim.

The mutual consent about the structure of the XML documents and the data type definitions of its elements and attributes (like string, boolean, float) is achieved by a so-called XML Schema Document (XSD). This is an abstract collection of meta data about an XML document. Or, in other words, a "formalization of the constraints, expressed as rules or a model of structure [...]" [van der Vlist, 2002]. More in-depth information about XSD's can be found at [World Wilde Web Consortium www pages, accessed June 2010].

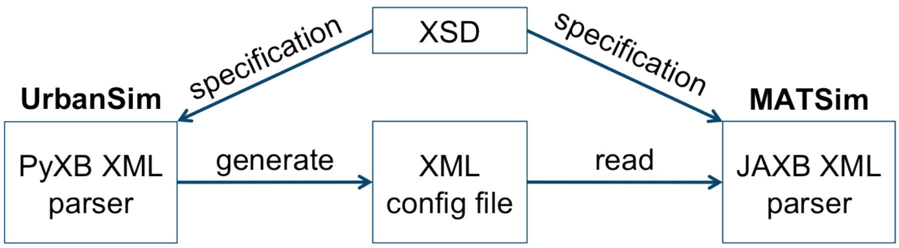


Figure 41: A XSD is used to generate and update customized XML parsers in MATSim and UrbanSim that read, write and validate XML documents.

Technically, the XSD is used to generate and update customized XML parsers in MATSim and UrbanSim that read, write and validate XML documents as depicted in Fig. 41. This is realized by additional software packages, PyXB and JAXB. PyXB is an acronym for Python W3C XML Schema Bindings. It is needed on the UrbanSim side to generate so called binding classes, i.e., an XML parser, built on the the given XSD specification. Analogously, JAXB is used in MATSim; it stands for Java Architecture for XML Binding. Reading or generating XML documents by these XML parsers automatically include a validation.

Given the XML parsers, UrbanSim creates an instance of its binding class and fills it with the MATSim settings from the transport model section of the UrbanSim configuration. This is transformed (marshaled) into an XML document and saved as a file. In MATSim, the XML file is read and parsed into Java objects of the MATSim XML parser including the parameter settings provided by UrbanSim. Finally, MATSim applies the parameter settings, i.e., puts the settings into MATSim specific configuration objects.

The XML processing in both UrbanSim and MATsim can be adapted to the new requirements, e.g., when introducing new parameter, by adapting the XSD and re-generating the XML parser via PyXB and JAXB. Minor adjustments, for example filling the binding objects with parameters from the travel model section, need to be done manually.

Overall, this approach provides a robust and reliable file-based communication between UrbanSim and MATSim and allows quick and convenient changes of the XML configuration structure if required.

For the sake of completeness, another software package, "generateDS", should be mentioned at this point. The acronym stands for Generate Data Structures from XML Schema. It was considered as an alternative for PyXB. In a short test it was found that generated XML documents did not contain any XML-header. Thus, this option was not investigated in more detail.

For more detailed information on PyXB, JAXB and generateDS, please refer to the project websites [PyXB www pages, accessed June 2010; JAXB www pages, accessed June 2010; generateDS www pages, accessed June 2010].

A.4 OBJECT-BASED COUPLING

As mentioned above, it is desirable to communicate directly at an object-based-level between UrbanSim and MATSim. This means to invoke, initialize and execute MATSim by UrbanSim like other UrbanSim routines and to exchange data, such as current land use information in UrbanSim or computed access and accessibility indicators by MATSim, directly via the main memory.

The reader may recall that UrbanSim and MATSim are implemented in different programming languages: Python and Java. At this point, it is useful to highlight that both programming languages are very different. Some notable constraints for interaction at the object level are listed as follows: The most important constraint is the different and incompatible byte code representation. Java programs are translated into Java byte code that is executed by the Java Virtual Machine (JVM). The reference implementation Python is written in C, called CPython. Analog to JVM, CPython compiles Python source code into Python byte code. For a discussion of Java-based implementations of Python see below. Another distinction is that Java employs static typing where type checking is performed during compile time as opposed to run-time in dynamic typing languages like Python. As a last example, Java provides basic data types like int, float, double, char and boolean in contrary to Python, where even basic data types are objects.

Despite these and other unnamed constraints, Python and Java can still communicate and work with each other via interfaces or additional software packages. At this point, solutions that satisfy the following requirements are considered:

1. Java routines must be callable from Python.
2. Like Java or Python, also the interoperability between both programming languages need to be platform independent, i.e., to support common platforms such as Windows, Mac and Linux.

Solutions that meet the requirements are presented below. Afterwards, some projects are presented that allow to communicate between Java and Python but do not fit the requirements.

JAVA NATIVE INTERFACE (JNI) The JNI is a native programming interface for Java programs. It allows Java code that run inside a JVM to interoperate with applications and libraries written in other programming languages, see Fig. 42. In order to call native applications and libraries out of the JVM, it is required to implement an additional software layer in C. This additional software layer causes some extra maintenance effort. This can be easily seen in the following steps summarizing the process to write a simple Java application that prints a message on the screen via a C program. A more detailed description is given in [Liang, 1999]:

1. Create a Java class that declares a native method.
2. Compile this class.
3. Create a C header file that defines the interface for the C implementation (generated by the "javah" compiler).
4. Write the C implementation of the native method. The implementation must follow the header file.
5. Compile the C implementation into a native library.
6. Run the Java application. Both the Java class and the native library are loaded at run-time and can be executed.

Interfacing Java with the Python interpreter (CPython) would need much more work implementing such software layer, e.g., to consider a meaningful handling for different data types. This implementation alone would be a large project for itself. It is partly solved by several projects presented in the following sections.

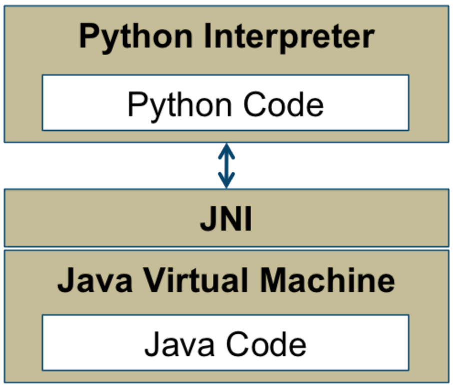


Figure 42: Communication between CPython and the Java Virtual Machine via JNI.

JPYPE The JPype project allows Python full access to Java class libraries. This is achieved through interfacing the Python interpreter (CPython) and the JVM at the native level using JNI and PNI (Python Native Interface) [JPype www pages, accessd june 2010] as shown in Fig. 43. So the extra development effort to implement an own software layer like for JNI is no longer necessary. In addition, JPype is available for prevalent platforms like

Windows, Mac and Linux, and it is convenient to use. Figure 44 and 45 illustrate a simple Python application that prints a string message in Java. To do so, it is necessary to import JPype in Python and to open and to close the connection to the JVM via *startJVM* and *shut-downJVM*. In order to call the Java methods *printOut*, *setString* and *getString* of the Java test class, presented in Fig. 45, it is necessary to set the class path where the desired Java classes are stored. Python accesses the *test* Java package, via *jpype.JPackage('test')* in order to create an instance of the Java *Test* class.

However, some limitations should be considered using JPype, e.g., the type conversion while translating between Python and Java. At this point, two short examples regarding the limitations of the type conversion are given. A detailed overview can be found in the JPype user guide [JPype User Guide, accessed June 2010].

JPype converts a Python object like an integer into the Java native types of byte, short or int according to the size of the value. Since Java allows overloading a method, opposed to Python, JPype is sometimes unable to decide which method to call. JPype provides wrappers like JByte, JShort, JInt, etc., to convert a Python values explicitly. But in the end, the developer is responsible to resolve those ambiguities. At this point, another example is provided for simple data structures such as arrays. The JArray wrapper class allows Python to receive arrays from Java or to pass arrays to Java. To create such an wrapper object, the (i) array type, the (ii) number of dimensions and the (iii) actual number of elements in the array are needed. Again, the developer is responsible to provide the correct information for the JArray and to make sure that the array provided as an argument for Java methods matches with the declared dimension and type. Convenient, resizable arrays having entered high level progamming languages in recent years could not be used for Python/Java data interchange.

Those limitations should be kept in mind while creating even more complex objects.

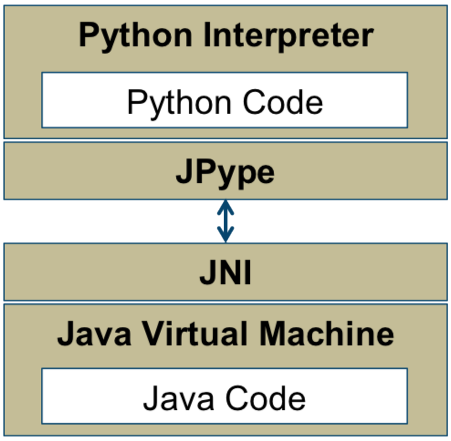


Figure 43: Java to Python integration after [Schreiber, 2009].

OTHER OBJECT-BASED INTEGRATION METHODS In this subsection, four alternative methods are presented to link Python with Java. These are JEPP and **Jython!**that, however, do not fit the requirements mentioned above to integrate MATSim into UrbanSim, but are briefly presented for completeness.

```python
import jpype
import os.path

classpath = os.path.join('/path/to/java/classes')   # set class path
jpype.startJVM(jpype.getDefaultJVMPath(), "-Djava.class.path=%s" % classpath)
testPkg = jpype.JPackage('test')                    # get the package
Test = testPkg.Test                                 # get the class
t = Test()                                          # create an instance of the class
t.printOut("This is a test message")                # call the printOut method
t.setString("Hello World")                          # set a string
s = t.getString()                                   # get the string back
print s                                             # show the received string (it contains "Hello World")
jpype.shutdownJVM()                                 # close JVM connection
```

Figure 44: A simple Python application using Java via JPype.

```java
package test;

class Test {
    private String msg; // stores a message from the python program

    // prints a message on screen
    public void printOut(String msg) {
        System.out.println(msg);
    }
    // stores a string
    public void setString(String s) {
        msg = s;
    }
    // returns the stored string
    public String getString() {
        return msg;
    }
}
```

Figure 45: A simple Java class with public methods.

JEPP is an acronym for Java Embedded Python. It embeds the CPython interpreter in Java via JNI, see Fig. 46, and allows Java to control Python applications, to evaluate Python statements and to execute Python scripts. In contrast to JPype, JEPP allows Java to invoke CPython, which is the opposite calling direction in order to call MATSim, written in Java, by UrbanSim, which is implemented in Python. For more information about JEPP refer to [JEPP www pages, accessed June 2010].

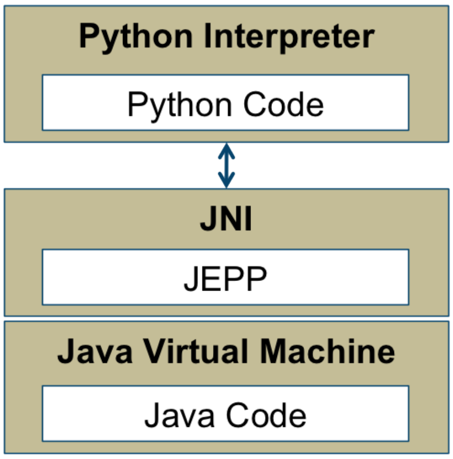


Figure 46: JEPP links CPython with Java via JNI after [Schreiber, 2009].

Jython, formally known as JPython, is another production-quality Python implementation such as CPython. Jython is a pure Java implementation of the Python interpreter. It consists of a Python compiler that compiles Python source code into Java byte code which runs on a JVM as shown in Fig. 47. Jython allows to mix and match Python code and Java code and to use Python to script Java applications. Also, Python can be used from Java applications. Moreover, Jython can be used interactively like the Python command shell. Almost all modules of the standard Python language, originally implemented in C, are part of Jython, except for the standard modules to create user interfaces. Those must be written in Java Swing, AWT (Abstract Window Toolkit) or SWT (Standard Widget Toolkit) [Jython www pages, accessed June 2010; Pedroni and Rappin, 2002].

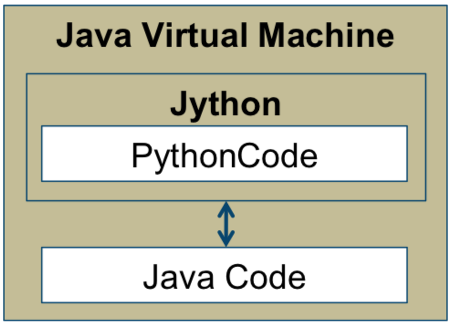


Figure 47: Jython is a pure Java implementation of the Python interpreter after [Schreiber, 2009].

A.5 DISCUSSION

To recall, the main requirements for integrating MATSim with UrbanSim are:

- To achieve a robust software integration.
- To achieve a convenient and less error-prone configuration of MATSim and UrbanSim.

The latter point is addressed by providing a centralized joint configuration for both frameworks as explained above. The following focuses on the introduced integration options:

OBJECT-BASED COUPLING The following approaches to interface Java with Python were introduced:

- The main disadvantage of *JNI* is to implement and maintain an additional software layer, e.g., to allow Python to access Java classes and libraries. The implementation of the software layer is carried out by an additional programming language, C, besides Python and Java. The layer needs to be adapted or at least re-compiled to run on different platforms. In consequence, this approach causes an increased effort while implementing, extending and testing the UrbanSim and MATSim integration compared to the status quo.
- The *JPype* aims to reduce the implementation and maintenance effort compared to JNI; e.g., no additional programming language is necessary and it does not need be adapted to different platforms by the developer or user. But like JNI, JPype can be considered as an additional software layer and due to the translation process on the native level between Python and Java, the software complexity still increases. The loose documentation including several spelling mistakes lets JPype appear to be immature.

- The following methods are not applicable to integrate MATSim into UrbanSim. *JEPP* allows Java to invoke CPython, which is the opposite calling direction that would be necessary. *Jython* would be a very interesting way to couple Java and Python, but it lags behind CPython regarding processing speed and even more importantly it does not allow access to a number of Python extensions like numpy or scipy that are extensively used in UrbanSim and only available for CPython.

In general, it can be stated that the software complexity increases by additional software layers. This implies either an increased implementation and maintenance effort or at least a less robustness.

FILE-BASED COUPLING The proposed file-based approach combines many advantages. It provides a robust and reliable file-based communication between UrbanSim and MATSim through data binding via PyXB and JAXB plus the validation via XSD. The concept of a file-based communication is easy to understand, it is platform-independent and no additional programming languages are needed.

A.6 CONCLUSION

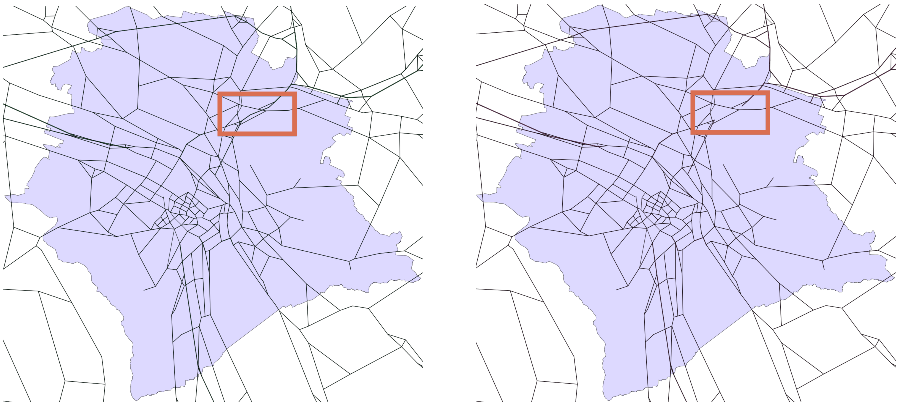
Among the object-based approaches, JPype can be seen as the most promising solution to interface Python with Java: (i) It is applicable for prevalent platforms like Windows, Mac and Linux, (ii) compared with JNI it relieves the user from implementing native methods and (iii) it is convenient to deploy. Limitations such as type and object conversions are negligible since only simple objects between UrbanSim and MATSim need to be exchanged. However, the loose documentation could be a bottleneck in the implementation process, and the large number of spelling mistakes on the website and the documentation make JPype look immature. JPype is a promising project, but regarding the status quo it cannot be recommended as the standard way to couple UrbanSim and MATSim. Therefore, the proposed file-based approach is selected for integrating MATSim with UrbanSim.

The next chapter will test and analyze the application of the MATSim with UrbanSim integration in a real-world scenario.

APPENDIX

B

B.1 SENSITIVITY TO A MODIFICATION IN THE TRANSPORT SYSTEM



(a) Network used in the Base Scenario

(b) Network used in the Schöneichtunnel Scenario

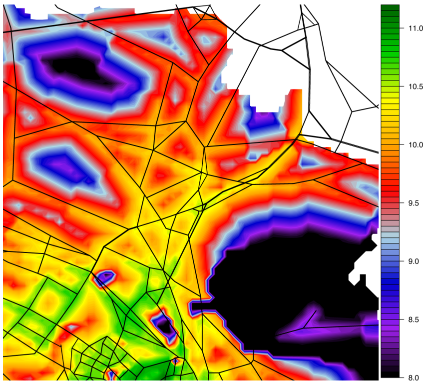
Figure 48: In order to investigate the impact of changes in the transport system, the "Schöneichtunnel" is closed by removing links from the road network as illustrated in Figure (b). Figure (a) shows the default, unchanged network.

In addition to the accessibility illustrations in Sec. 6.4, a sensitivity test using the same parameter settings as listed in Tab. 7 is performed to investigate the impact from changes on the road network on the accessibility outcome. For this purpose, two scenarios are created that only differ in the network set-up:

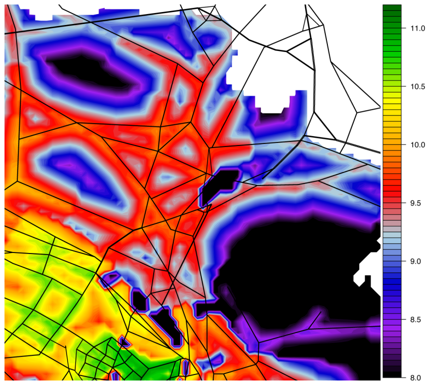
1. **Base Scenario**: The base scenario leaves the road network as it is.
2. **Schöneichtunnel Scenario**: In this scenario, the "Schöneichtunnel" – an important intersection-free artery connection in the western part of Zurich – is closed; see Fig. 48. It connects the north-easterly suburbs and the central business district with a capacity of 5'740 vehicles per h in each direction. There are no alternative roads that can compensate such a closure.

   The idea for this scenario is loosely based on a real closure of the Schöneichtunnel due to maintenance works in the year 2001 [Rederlechner, 2001].

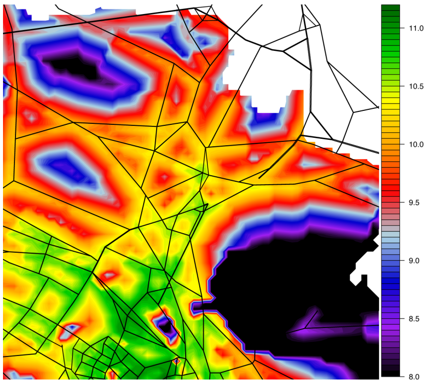
Both scenarios are using the output of the preparatory MATSim run, discussed in Sec. 6.3.3, as input and run for another 1000 iterations with the same time and route adaptation settings. This means: During the first 800 iterations, 10% of the agents perform "time adaptation", which changes the departure times of an agent, and 10% adapt their routes. The remaining agents switch between their plans. During the last 200 iterations, time and route adaptations are switched off. Thus, agents only switch between existing plans.



(a) Base Scenario after 1000 iterations



(b) Schöneichtunnel closure after 1 iteration

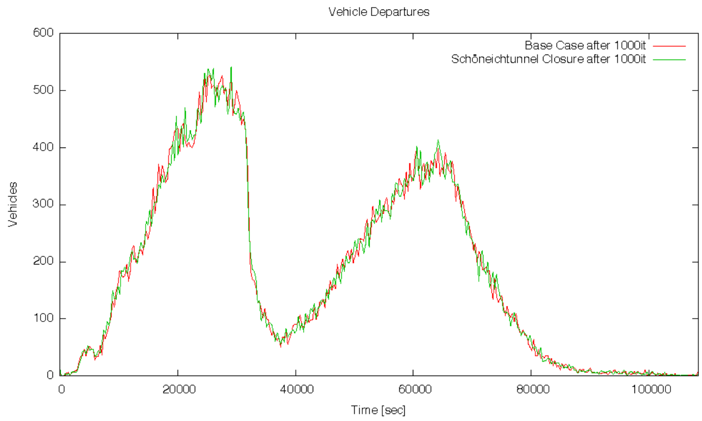


(c) Schöneichtunnel closure after 1000 iterations

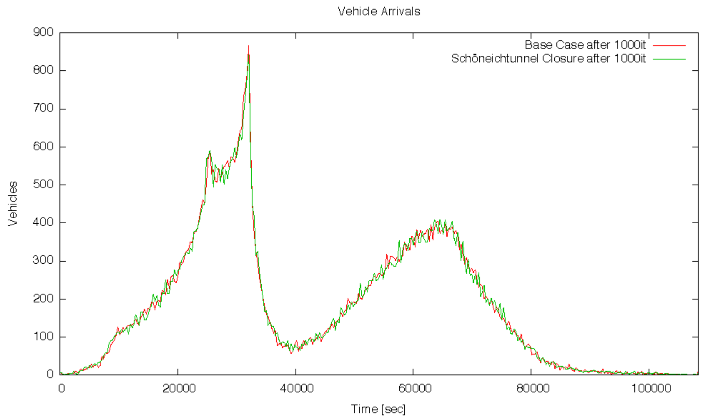
Figure 49: The sensitivity test illustrates the impact of a change in the transport system, simulated by a tunnel closure, on the accessibility measure. Note the reduction in accessibility on both ends of the closed tunnel immediately after closure (b). After 1000 iterations, there is no discernible difference to the base case (c). The color scale is different from the previous figures in order to highlight the differences between (a) and (b).

The value range in Fig. 49 is limited for visualization purposes. This means that only accessibility outcomes between the values 5 and 2 are plotted. Fig. 49a shows the **Base Scenario**. For Fig. 49b the following was done: (i) The tunnel was closed. (ii) For all routes that used the tunnel, an alternative route was computed, based on the free speed travel times, but minus the tunnel. (iii) A traffic flow simulation was run based on these routes. The result (Fig. 49b) is significantly reduced accessibility in the north-eastern sector of the city. Strong congestion upstream – parallel to where the tunnel was – significantly hinders car traffic. Fig. 49c then shows accessibility after the system had a chance to adjust to the closed tunnel. Surprisingly, there seems to be *no* accessibility consequences. Seemingly, the system re-equilibrates in a way that the status quo ante in terms of accessibility is recovered.

One might speculate that the effect of the tunnel closure manifests itself in the departure time choice. This would mean that accessibility during the peak period could remain virtually unchanged while at the same time the peak period itself would be extended. The simulation results were checked accordingly; it was not possible to identify any change in the departure time



(a) Comparing the departure times between Base Scenario and Schöneichtunnel closure after 1000 iterations



(b) Comparing the arrival times between Base Scenario and Schöneichtunnel closure after 1000 iterations

Figure 50: This shows the departure and arrival pattern for the Base and Schöneichtunnel scenario.

distribution (Fig. 50). The simulation results are, however, distinctly different since the average trip distances in the simulation area drop from 9800m to 9350m. Thus, the long-term effect of the tunnel closure seems to be a reduction in average trip distances, while the average travel times remain the same. This may seem a bit counter-intuitive. We have, however, seen similar results in previous studies. Presumably, a local change in a networked transport system can lead to a re-arrangement of the traffic patterns in such a way that it redistributes the effects of the change throughout the system; the overall effect is then a small but globally felt accessibility change Nagel [2008]; Balmer et al. [2009a]. In the present situation, there does not even seem to be that globally felt accessibility change; it may therefore be a real-world example of the Braess paradox Braess [1968]. Such results, however, do not hold in all situations; Ref. Nagel [2011] describes a modification where the gains and losses (albeit differently measured) show a clear spatial picture.

At this point, the following conclusion can be drawn: The proposed high resolution accessibility approach (Sec. 6.2) clearly visualizes accessibility changes after a major change in the transport infrastructure. Somewhat surprisingly, the infrastructure change (the removal of a major inner-urban freeway section) has no discernible effect after the system has equilibrated.

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