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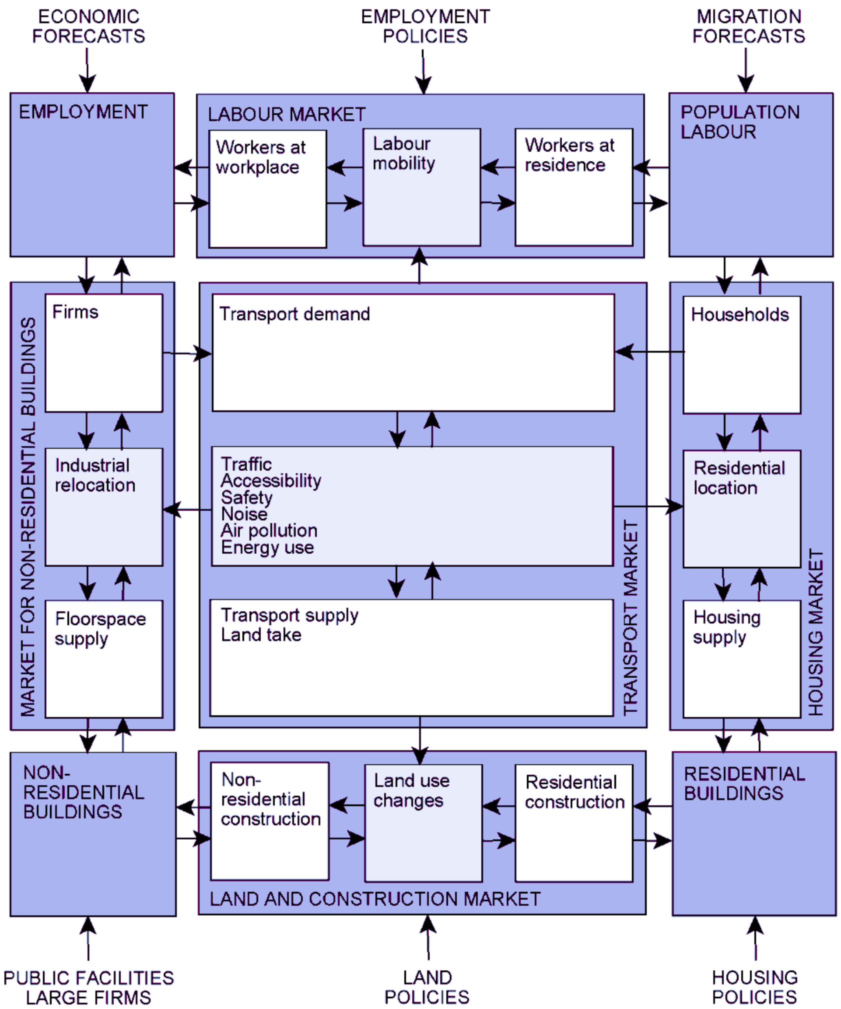
Michael Wegener

The IRPUD Model



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Spiekermann & Wegener
Urban and Regional Research (S&W)

Lindemannstrasse 10
D-44137 Dortmund
E-mail: suw@spiekermann-wegener.de
http://www.spiekermann-wegener.de/en

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Introduction

The IRPUD model is one of the few models of urban land use and transport developed in Germany (Wegener, 2004). It was designed and implemented since 1977 at the Institute of Spatial Planning of the University of Dortmund (IRPUD) and has been applied in major research projects:

- The projects "Intraregional Location and Mobility" and "Long-Range Agglomeration and Deglomeration Processes in the Eastern Ruhr Region" funded by the German Research Council aimed at analysing the long-term spatial development in the eastern part of the Ruhr agglomeration in Germany since its first urbanisation phase until its present suburbanisation phase and to forecast its likely future development with an integrated, newly developed mathematical model (Schönebeck et al., 1978; Gnad et al., 1983).
- The International Study Group on Land-Use Transport Interaction (ISGLUTI) aimed at investigating long-term effects of changes in the cost of public and private travel, the provision of major transport infrastructure and regulations and legislation affecting the location and density of activities on travel patterns, residential and industrial location, transport costs, efficiency pf the transport system, equity and energy use. In the study nine urban models were applied to a common set of policy scenarios for nine urban regions (Webster et al., 1988).
- The project PROPOLIS (Planning and Research of Policies for Land Use and Transport for Increasing Urban Sustainability) aimed at further developing theories on the interaction between transport and spatial development and the identification of measures to improve the sustainability of urban regions. For this three existing land use and transport models were further developed and used to forecast and evaluate the impacts of different policies on the sustainability of spatial development in seven urban regions in Europe (Lautso et al., 2004).
- The project "Spatial Scenarios for the Eastern Ruhr Area" was part of the project "Analysis of Central Constraints, Instruments and Goal Criteria for State Transport Planning in North-Rhine Westphalia" conducted by the Institut für Landes- und Stadtentwicklungsforschung und Bauwesen (ILS) for the Ministry for Transport, Energy and Regional Planning of the state of North-Rhine Westphalia. In the project the IRPUD model was used to simulate the impacts of different policy scenarios on land use and transport development (Spiekermann and Wegener, 2005).
- The project STEPs (Scenarios for the Transport System and Energy Supply and their Potential Effects) aimed at developing, comparing and assessing scenarios for the transport system and energy supply of the future in terms of security of energy supply, effects on the environment, the economy and technology and the impacts of measures to internalise external costs and the interactions between transport and spatial development. In STEPs five integrated models of spatial development for Europe and five urban regions were applied (Fiorello et al., 2006).
- The project "Criteria for Adequate Service of Public Transport in North-Rhine Westphalia", a cooperation with the universities of Wuppertal and Münster for the Ministry for Building and Transport of North-Rhine Westphalia, assessed the impacts of alternative rules for the allocation of public transport subsidies in North-Rhine Westphalia on mobility, accessibility and the environment for different types of regions (Brosch et al., 2007).
- In the project “Ruhr Area 2050: Modelling the Energy Transition in the Ruhr Area” funded by the Mercator Foundation (Schwarze et al., 2017) the database of the model was extended to the whole Ruhr Area and its planning horizon until the year 2050, and the model was extended by submodels for cycling as a separate mode, electro-mobility, car sharing and building energy and was used to forecast the impacts of land use and transport policies and of combinations of policies as integrated strategies on modal shift and CO_2 emissions.

In the future it is intended to extend the model by a submodel of local goods transport and to better integrate the existing environmental submodel.

1. Overview

The IRPUD model is a simulation model of intraregional location and mobility decisions in a metropolitan area (Wegener, 1982; 1983; 1985; 1086, 1994; 1996, 1999; Wegener und Spiekermann, 1996). It receives its spatial dimension by the subdivision of the study area into *zones* connected with each other by transport networks containing the most important links of the public transport and road networks coded as an integrated, multimodal network including all past and future network changes. It receives its temporal dimension by the subdivision of time into *periods* of one or more years' duration.

1.1 Model Structure

The model predicts for each simulation period intraregional *location decisions* of industry, residential developers and households, the resulting *migration* and *travel* patterns, *construction* activity and *land use* development and the impacts of *public policies* in the fields of industrial development, housing, public facilities and transport.

Figure 1.1 is a schematic diagram of the major subsystems considered in the model and their interactions and of the most important policy instruments.

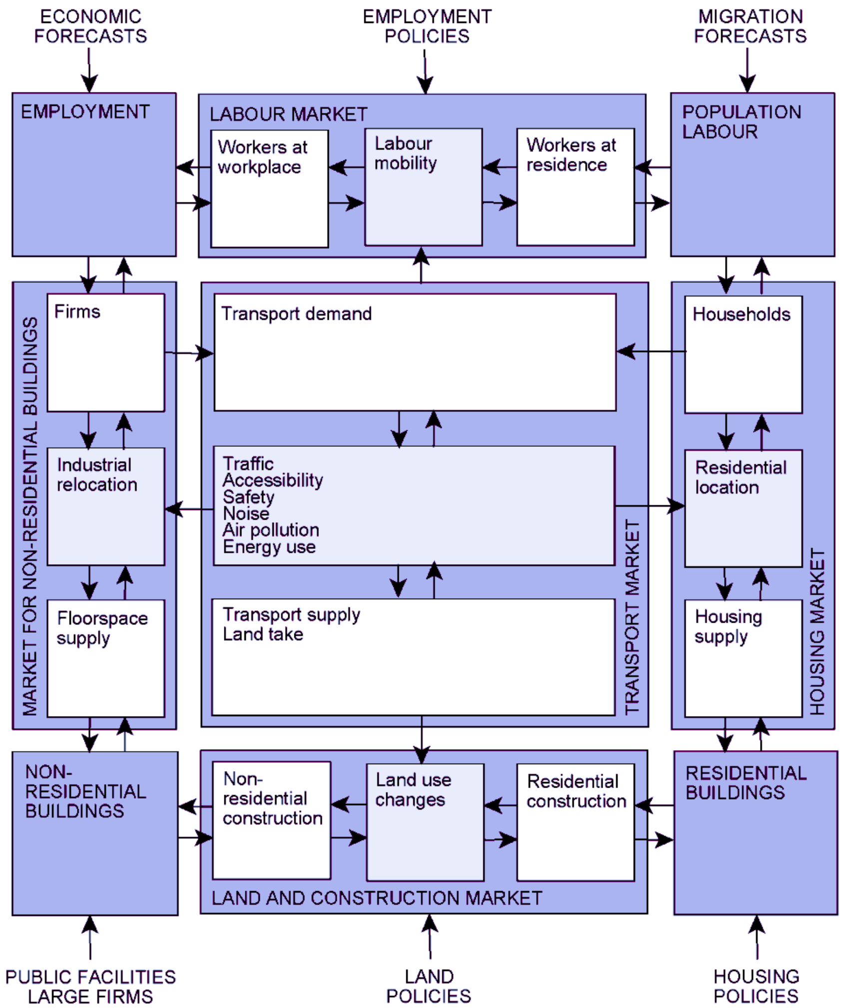

Figure 1.1. The IRPUD model

The four square boxes in the corners of the diagram show the major stock variables of the model: *population*, *employment*, *residential buildings* (housing) and *non-residential buildings* (industrial and commercial workplaces and public facilities). The actors representing these stocks are *individuals or households*, *workers*, *housing investors* and *firms*.

These actors interact on five *submarkets* of urban development. The five submarkets treated in the model and the market transactions occurring on them are:

- *labour market*: new jobs and redundancies,
- the *market for non-residential buildings*: new firms and firm relocations,
- the *housing market*: immigration, outmigration, new households and moves,
- the *land and construction market*: changes of land use through new construction, modernisation or demolition.
- the *transport market*: trips.

For each submarket, the diagram shows *supply* and *demand* and the resulting *market transactions*. Choice in the submarkets is constrained by supply (jobs, vacant housing, vacant land, vacant industrial or commercial floorspace) and guided by attractiveness, which in general terms is an actor-specific aggregate of *neighbourhood quality*, *accessibility* and *price*.

The large arrows in the diagram indicate exogenous inputs: these are either *forecasts* of regional employment and population subject to long-term economic and demographic trends or *policies* in the fields of industrial development, housing, public facilities and transport.

1.2 Submodels

The IRPUD model has a modular structure and consists of six interlinked submodels operating in a recursive fashion on a common spatio-temporal database:

(1) The *Transport Submodel* calculates work, shopping, services/social and education trips for four socioeconomic groups and four modes, car/motorcycles, public transport, cycling and walking. It determines a user-optimum set of flows where car ownership, trip rates and destination, mode and route choice are in equilibrium subject to congestion in the road network.

(2) The *Ageing Submodel* computes all changes of the stock variables of the model which are assumed to result from biological, technological or long-term socioeconomic trends originating outside the model (i.e. which are not treated as decision-based). These changes are effected in the model by probabilistic ageing or updating models of the Markov type with dynamic transition rates. There are three such models, for employment, population and households/housing.

(3) The *Public Programmes Submodel* processes a large variety of public programmes specified by the model user in the fields of employment, housing, health, welfare, education, recreation and transport.

(4) The *Private Construction Submodel* considers investment and location decisions of private developers, i.e. of enterprises erecting new industrial or commercial buildings, and of residential developers who build flats or houses for sale or rent or for their own use. Thus the submodel is a model of the regional land and construction market.

(5) The *Labour Market Submodel* models intraregional labour mobility as decisions of workers to change their job location in the regional labour market.

(6) The *Housing Market Submodel* simulates intraregional migration decisions of households as search processes in the regional housing market. Housing search is modelled in a stochastic microsimulation framework. The results of the Housing Market Submodel are intraregional migration flows by household category between housing by category in the zones.

Figure 1.2 visualises the recursive processing of the six submodels. The Transport Submodel is an equilibrium model referring to a *point in time*. All other submodels are incremental and refer to a *period of time*. Submodels (2) to (6) are executed once in each simulation period, while the Transport Submodel (1) is processed at the beginning and the end of each simulation period. Each submodel passes information to the next submodel in the same period and to its own next iteration in the following period

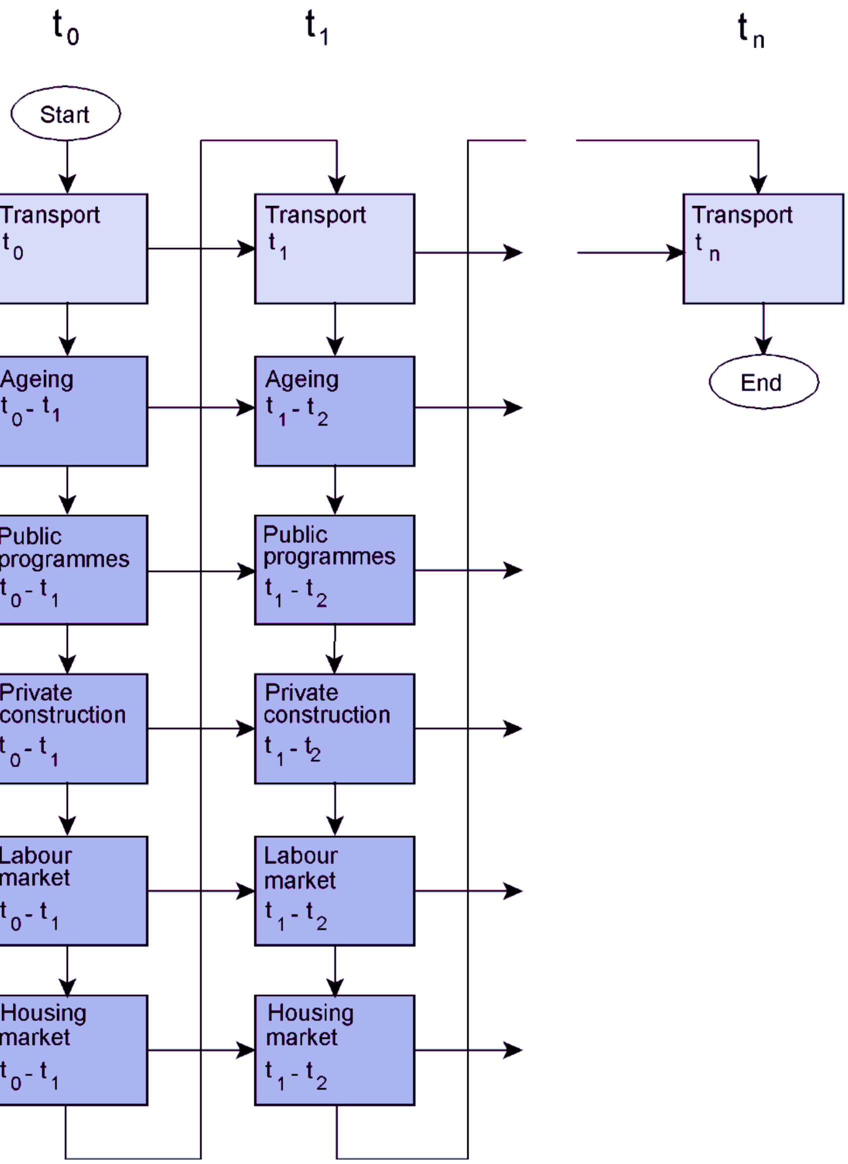

Figure 1.2. Recursive processing of submodels

2. Theoretical Approach

The IRPUD model is an integration of *technical*, *economic and social* theories of urban development (Fürst and Wegener, 1999):

2.1 Technical Theories: Urban Mobility Systems

Technical theories of urban development interpret cities as urban mobility systems. In the 1950s first efforts were made in the USA to study the interrelationship between transport and the spatial development of cities. Hansen (1959) was able to demonstrate for Washington, DC that locations with good accessibility had a higher chance of being developed, and at a higher density, than remote locations ("How accessibility shapes land use"). The recognition that trip and location decisions co-determine each other and that therefore transport and land use planning needed to be co-ordinated, quickly spread among American planners, and the 'land-use transport feedback cycle' became a commonplace in the American planning literature. (see Figure 2.3):

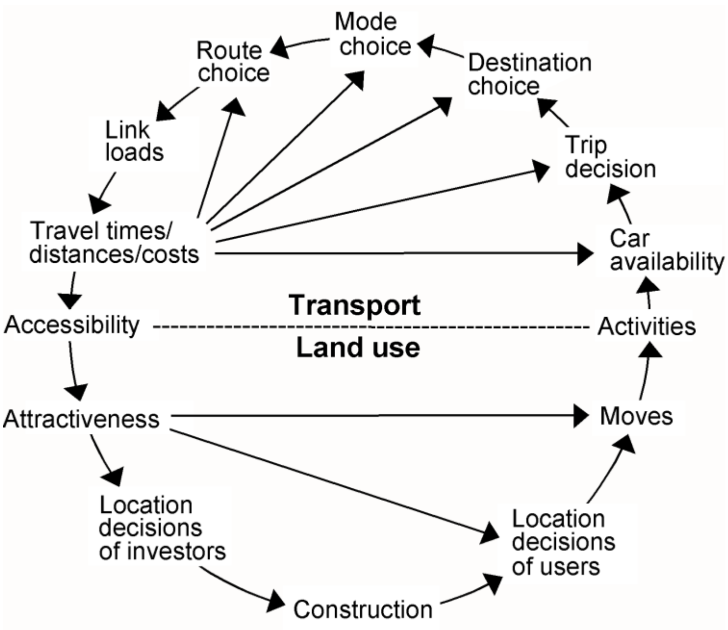

Figure 2.3. The land-use transport feedback cycle.

The set of relationships implied by the land-use transport feedback cycle can be briefly summarised as follows

- The distribution of *land uses*, such as residential, industrial or commercial, over the urban area determines the locations of human *activities* such as living, working, shopping, education or leisure.
- The distribution of human *activities* in space requires spatial interactions or trips in the *transport system* to overcome the distance between the locations of activities.
- The distribution of infrastructure in the *transport system* creates opportunities for spatial interactions and can be measured as *accessibility*.
- The distribution of *accessibility* in space co-determines location decisions and so results in changes of the *land use* system.

2.2 Economic Theories: Cities as Markets

A second set of theories focuses on the *economic* foundations of city growth. Following this paradigm, it is the market function that distinguishes the city from the countryside. A fundamental assumption of all spatial economic theories is that locations with good accessibility are more attractive and have a higher market value than peripheral locations. Probably the most influential example of the latter kind is the model of the urban land market by Alonso (1964). The basic assumption of the Alonso model is that firms and households choose that location at which their bid rent, i.e. the land price they are willing to pay, equals the asking rent of the landlord, so that the land market is in equilibrium. So it is not surprising that, say, jewellers are found in the centre, whereas trucking companies have their yards on the periphery. Alonso's model has been the point of departure for a multitude of urban economics model approaches. In more advanced variations of the model, restrictive assumptions such as perfect competition and complete information or the monocentric city have been relaxed.

In the past low energy prices, rising incomes, more working women, smaller households, more leisure time and changes in housing preferences have created a demand for more spacious living in attractive neighbourhoods, and this has been easier to realise on the urban periphery, preferably in the vicinity of small towns with attractive town centres and up-market shopping facilities. Retail and service facilities have continued to follow their clients to the suburbs, as the new 'clean' industries which depend on the highly skilled middle-class labour living in the suburbs.

From a social and environmental point of view the results of this deconcentration process are generally considered to be negative: longer journeys to work and shopping trips, more energy consumption, pollution and accidents, excessive land consumption and problems of public transport provision in low-density areas. A dispersed settlement structure relies on access to car travel as a prerequisite for taking advantage of employment and service opportunities, and thus contributes to social segmentation. Inner cities, except for the largest and most successful metropoles with a prosperous, 'international' central area, are victims of the exodus of people and jobs and can at best hope to survive as one among several regional centres. Inner-city housing areas become marginalised as the younger and more active segments of the population leave because of the run-down housing stock, traffic noise and lack of parking space, unless the total existing population is displaced by gentrification or tertiarisation – though these are themselves signs of economic prosperity and hence occur predominantly in successful cities.

However, there are tendencies potentially working into other directions. Teleworking and teleshopping are still in their infancy but may fundamentally change daily mobility patterns and hence location behaviour. There is a growing diversity of life styles and housing preferences which may challenge the dominance of suburban living as the ultimate manifestation of the 'good life'. There are signs of a re-appreciation of urban life and a trend to return to inner cities. On the other end of the spectrum, there are new ideas in urban and landscape design towards new forms of integration of housing and nature under ecological perspectives.

2.3 Social Theories: Society and Urban Space

In social sciences theories of urban development the spatial development of cities is the result of individual or collective appropriation of space. Hägerstrand (1970) made these ideas operational by the introduction of 'time budgets', in which individuals, according to their social role, income and level of technology (e.g. car ownership) – subject to various types of constraints – command *action spaces* of different size and duration.

Action spaces are limited by three types of constraints:

- *capacity constraints*: personal, non-spatial restrictions on mobility, such as monetary budget, time budget, availability of transport modes and ability to use them,
- *coupling constraints*: restrictions on the coupling of activities by location and time schedules of facilities and other individuals,
- *institutional constraints*: restrictions of access to facilities by public or private regulations such as property, opening hours, entrance fees or prices.

On the basis of action-space theory, Zahavi (1974) proposed the hypothesis that individuals in their daily mobility decisions do not, as the conventional theory of travel behaviour assumes, *minimise* travel time or travel cost needed to perform a given set of activities but instead *maximise* activities or opportunities that can be reached within their travel time and money budgets. He studied a large number of cities all over the world and found that the time and money budgets devoted to transport vary within urban regions as a function of age, income and residential location but show a remarkable stability over time when averaged across whole urban regions. The stability of time and money budgets for transport explain why in the past gains in travel speed have not been used for time savings (as is usually assumed in transport cost benefit analysis) but for more and longer trips.

It also explains why the fact that over the last forty years in most European countries until very recently petrol prices have declined by more than half in real terms has not led to a reduction in travel expenditure but to a vast expansion in automobile travel. Zahavi's theory finally explains why acceleration and cost reduction together permit more and more people to choose residential locations on the far periphery of urbanised areas, without increasing their time and money budgets for travel, and why shopping centres in sparsely populated peripheral locations are able to attract customers from larger and larger catchment areas. The theory of time and travel budgets permits to speculate what would happen if speed and cost of travel were significantly changed by environment-oriented planning policies. Acceleration and cost reduction in transport lead to more, faster and longer trips; speed limits and higher costs lead to less, slower and shorter trips. In the long run this has effects on the spatial structure.

2.4 Theory Integration

The IRPUD model is an attempt to combine the above three families of theories in one integrated, dynamic modelling framework. By dynamic it is implied that the model does not assume that urban systems are in equilibrium but that various processes of different speed interact so that partial equilibria may be approached but in reality is rarely achieved. For this the model distinguishes between slow, medium-speed and fast processes:

Slow processes:	transport construction non-residential construction residential construction
Medium-speed processes:	economic change demographic change technological change
Fast processes:	labour mobility residential mobility daily mobility

The response time and duration of these processes vary between a few hours and a human lifetime or more. The differences in speed are taken account of in the model by inserting different delays between their stimulus and response.

In addition, urban change processes can be classified by causation and type of actors: Choice processes are the outcome of location or mobility decisions by private actors. *Transition* processes are changes from one state to another in the course of time. *Policy* processes are the result of regulatory or investment decisions by public authorities.

Public actors in urban development are governments and government agencies from the local to the national level. Public interventions constitute the *policy* component of urban development. *Private* actors in urban development are firms, households or individuals. Their decisions constitute the *market* component of urban development. In the model only market choices and time-dependent transitions are modelled endogenously; public policies are entered exogenously. However, 'large' decisions by private actors, such as a decision to build a new car assembly plant or to close an existing one are included under policies, even though they are not in the strict sense public decisions.

Accordingly, the model predicts primarily the behaviour of private actors. It is assumed that private actors *attempt* to act *rationally*, i.e. to perceive and accomplish their preferences, are subject to group-specific economic, institutional and informational constraints and act as 'satisficers', i.e. are content with suboptimum *aspiration levels*. These assumptions are modelled as follows:

The *preferences* of actors are modelled as multi-attribute utility functions. A multi-attribute utility function specifies how attributes of a choice alternative contribute to its attractiveness or utility relative to other alternatives in the choice set.

The *constraints* are modelled in a variety of ways:

- *Economic* constraints are usually expressed as monetary budgets such as the housing or travel budgets of households. Sometimes they are defined as thresholds. For instance, firms are assumed not to select a location if the land or building costs exceed a certain percentage of their turnover.
- *Institutional* constraints in general restrict the choice set. For instance, households above a certain income are not eligible to move into public housing. Those without a driving licence, such as children, cannot drive a car.
- *Informational* constraints also restrict the choice set. One example is that households looking for a dwelling inspect only a limited number of dwellings before making a choice. In other choice contexts, uncertainty and lack of information is implied in the choice model.

Preferences and constraints are different for each group of actors because of their different income, social status, position in the life cycle, education or occupation. Preferences and constraints are used to model *decision situations* in which actors choose among options under constraints. It is assumed that the choice pattern conforms to the principles of random utility maximisation. Random utility maximisation suggests that the utility of a choice alternative is composed of a deterministic and a random component. The deterministic component is the utility calculated in the attractiveness function. The random component takes account of factors preventing a completely rational choice such as uncertainty, lack of information or factors which are not specified in the attractiveness function or have to do with the dispersal of preferences among the individual actors in a group of actors. Choices can themselves be alternatives in a choice set, i.e. can be hierarchically nested.

3. Transport Submodel

The *Transport Submodel* calculates work, shopping, services/social and education trips for four socio-economic groups and four modes: car/motorcycle, public transport, cycling and walking. The model seeks to determine a user-optimum set of flows where car availability, trip rates and destination, mode and route choice are in equilibrium subject to congestion in the road network.

The *Transport Submodel* therefore serves to model the mobility pattern in the region. In addition it is important for the land use parts of the model as it provides accessibility indicators that are part of the attractiveness functions in both the *Private Construction Submodel* and the *Housing Market Submodel*.

3.1 Overview

The *Transport Submodel* establishes congestion-sensitive, user-optimum network equilibrium by proceeding in eight steps:

(1) In the *trip generation* step, trip origins and destinations are calculated as a function of origin and destination activities.

(2) The *car-availability* model estimates the number of cars owned in each zone by each socio-economic group as a function of household travel budgets and expected travel expenses including electric and car-sharing cars.

(3) In the *network analysis* for each mode and pair of zones the shortest route through the appropriate network is determined. In the public transport network, transfers between lines are automatically effected taking account of access and waiting times.

(4) For these optimum routes, *trip utilities* (total benefit less cost of each trip) are calculated for each household travel budget group.

(5) In the *trip distribution* step traffic flows between zones by mode and purpose are estimated as a function of origins and destinations and trip utilities. The trip distribution model is doubly constrained for work and school trips, but singly constrained for shopping and service trips.

(6) In the *modal split* step modal shares are calculated for each origin-destination relation and each household travel budget group based on the comparison of trip utilities. The model assumes that all available cars may potentially be used for work trips and that there are captive users for either public transport or walking.

(7) In the *trip assignment* step trips are loaded on the links of the shortest routes determined for each mode.

(8) The *capacity-restraint* step adjusts link travel times of congested road links using a speed-flow relationship.

(9) Network capacity-flow equilibrium is approached by executing steps (2) to (8) several times and at each iteration adjusting car ownership, trip rates and destination, mode and route choice following a generalisation of the algorithm by Evans (1976).

After the last iteration, steps (3) and (4) are executed one more time to yield trip utilities of the loaded network. Figure 3.1 is a flow diagram of the *Transport Submodel*.

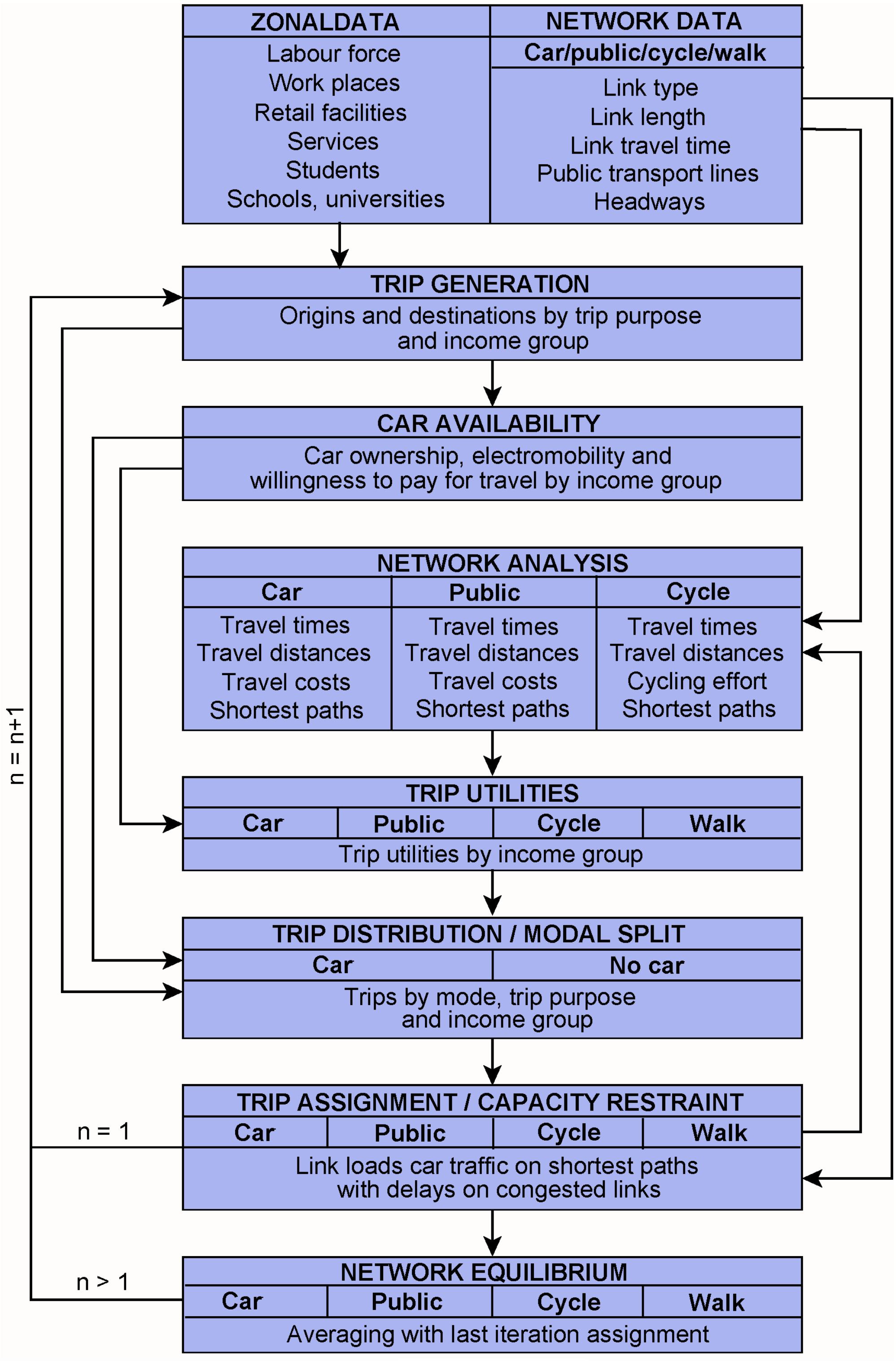

Figure 3.1. Transport Submodel: flow diagram

3.2 Transport Supply

Transport supply is represented in the model by two explicit transport networks, road and public transport, and two implicit networks, cycling and walking.

Networks

The road and public transport networks are coded as separate networks by link. Link data include the usual information such as link type, directions, length, travel time or travel speed, frequency of service and lines (public transport only). Each zone is connected with both networks by at least one access link.

The model currently can handle 1,200 internal and external zones, 60,000 two-way links (30,000 nodes) in each of the road, public transport and cycling network and 3,000 public transport lines. Up to eight public transport lines can run on one link. All three transport networks can be incrementally updated during a simulation by exogenously specifying time-sequenced network changes by link.

Modes

The four transport modes represented in the model comprise the following link types:

Car/Motorcycle (m = 1)

0 access link, internal link
1 Autobahn (motorway), six-lane
2 Autobahn (motorway), four-lane
3 urban motorway, four-lane
4 urban thoroughfare, four-lane
5 urban thoroughfare, two-lane
6 urban local road, two-lane
7 rural road, two-lane

Public Transport (m = 2)

0 access link, internal link
1 local train
2 S-Bahn (rapid transit)
3 U-Bahn (underground)
4 tramway
5 bus

Cycling (m = 3)

0 cycling

Walking (m = 4)

0 walking

Time of Day

The model simulates all outgoing home-based trips during a four-hour morning peak period. Return trips and non-home-based trips are not considered. The link travel times coded in the road network refer to non-congested travel. The levels of service coded in the public transport network (train/bus frequencies) apply to the four-hour morning peak period.

Parking

Parking difficulties in high-density areas with limited parking facilities are taken account of by (a) a time and cost penalty for trips ending in such areas and (b) a monthly cost penalty for car owners living in such areas. The parking search time and parking costs of (a) are estimated as a function of parking supply v. parking demand, the latter being based on results of the car ownership model plus additional parking requirement standards for employment, shops, services and public facilities. The monthly costs of having a downtown garage of (b) is calculated as a fixed multiple of short-term parking costs.

Transport Costs

Travel time and travel costs are calculated differently for each of the four modes considered in the model:

Car/Motorcycle (m = 1)

Travel times on the road network are determined using a time-oriented minimum-path algorithm. Door-to-door travel times produced by the algorithm include: access time, in-vehicle time and terminal time. Travel distances of minimum-time routes are also recorded. Intrazonal travel times and distances are exogenous inputs. Car travel costs are distance-dependent out-of-pocket car operating costs divided by average car occupancy and are inflated by a rate reflecting inflation and the development of petrol prices. In a final step, car travel times and costs are incremented by parking search time and parking costs at trip ends. Car travel times and costs, and thus the trip utilities of car trips, are recalculated several times during the traffic assignment process with different link loads and hence link travel times at each iteration.

Public Transport (m = 2)

Travel times on public transport are determined using a time-oriented minimum-path algorithm which adds boarding and transfer waiting time to in-vehicle travel time as a function of the service frequency of the connecting line. Door-to-door travel times produced by the algorithm include the following components: access time, waiting time before boarding, in-vehicle travel time, waiting time at transfer stops (if any), terminal time. Also the travel distances of the minimum-time routes are recorded. Intrazonal travel times and distances are exogenous inputs. Travel costs of public transport trips are calculated as a flat fare plus a distance-dependent fare increment for longer trips and are reduced by a discount factor reflecting savings made by buying monthly tickets. All fare components are inflated by an appropriate inflation rate. Public transport travel times and costs remain unchanged during the traffic assignment iterations.

Cycling (m = 3)

Door-to-door travel times in the cycling network are determined using a time-oriented minimum-path algorithm. The costs of bicycle trips are zero.

Walking (m = 4)

Because there is no explicit network of walkways contained in the model, door-to-door walking/cycling time between two zones is inferred by taking the minimum of the travel distances of the three other modes, reducing it by a detour factor (because walking/cycling trips are more direct than cycling lanes), and converting it into time through division by walking speed. The costs of walk/bicycle trips are zero.

Non-Monetary Characteristics of Transport

The most important non-monetary characteristics of transport supply considered in the model are travel time and comfort. Frequency of public transport service is integrated into travel time in the form of waiting time. Travel time is *not* converted to transport cost by value-of-time coefficients, but both, travel time and travel cost, are mapped into a common utility dimension by value functions. Differences between modes not captured by the dimensions time and money (e.g. comfort, physical effort, reliability, safety) are reflected in different value functions for the three modes. Comfort is a fixed indicator between 0 and 100 characterising the attractiveness of the four modes.

3.3 Travel Demand

The travel demand submodel is an aggregate spatial interaction model with the following eight steps:

(1) Trip Generation

In a first step, initial estimates of trip origins and destinations are calculated as a function of zonal activity levels. Only home-based trips are considered. The model disaggregates trips by four trip purposes *g* and four household income groups/skill levels *q* (Table 3.1):

Table 3.1. Classification of trips

	Trip purpose *g*	Income group/ skill level *q*	Origin activity	Destination activity
1	Work	1 2 3 4	Workers of skill level *q*	Jobs of skill level *q*
2	Shopping	1 2 3 4	Households of income group *q*	Retail employment
3	Services/ social	1 2 3 4	Households of income group *q*	Service employment, population
4	Education	1 2 3 4	Students of households of income group *q*	Secondary schools (classes)

The above sixteen travel demand models are classified into 'mandatory' and 'voluntary' trips:

- *Mandatory* trips are work trips (g = 1) and education trips (g = 4). Their numbers, or origins, are assumed to be fixed by a daily trip rate per worker or student, respectively.

- *Voluntary* trips are shopping trips (g = 2) and service/social trips (g = 3). Demand for such trips is elastic, i.e. depends to a certain degree on transport supply and travel budgets. Poor people can afford fewer cars and can make fewer (and cheaper) voluntary trips than rich people who can afford more cars and make more (and more expensive) trips. Thus trip origins for shopping and service/social trips in the model are a function of activity levels and car ownership. Car ownership, however, is a function of trip expenditure and thus of destination and mode choice (see below). Hence, the trip generation step is included in the iterations of the traffic assignment process (see below).

(2) Car Availability

In the car availability submodel the number of cars owned by households, including electric cars, and the number of car-sharing cars in each zone are calculated.

Car ownership

The submodel estimates the number of cars owned by households as a function of household travel budgets and expected travel expenditure:

$$C_{qi} = \frac{H_{qi}\ y_{qi} - \sum_{gjm} T_{qgijm}\ c_{ijm}}{o + p_i} \tag{3.1}$$

where C_{qi} is the number of cars owned by households of income group q living in zone i, H_{qi}, with a monthly travel budget y_{qi}, and o and p_i are monthly costs of owning and parking a car in zone i, respectively. The T_{qgijm} trips per month of households of type q for purpose g from zone i to zone j using mode m, and c_{ijm} are the out-of-pocket car operating costs of such trips. This equation reflects the assumption that households have to split their travel budgets between expenditures for trips and for cars.

Concurrently with car ownership levels, for each household income group in each zone, the amount of money the household is able and willing to pay given its car ownership level and number of trips is estimated as a deviation from the system mean travel cost c_o proportional to the deviation of the household's car ownership level from the regional average:

$$c_{oqi} = c_o \frac{C_{qi}\ /\ H_{qi}}{\sum_{qi} C_{qi}\ /\ \sum_{qi} H_{qi}} \tag{3.2}$$

where q_{oqi} is the trip cost standard as used in Equation 3.5 below. This equation reflects the assumption that households owning more (fewer) cars will also choose more (less) expensive trips.

Zonal household travel budgets y_{qi} are elastic to take into account that suburban households pay more for transport and less for housing than urban households. The number of monthly trips by purpose, destination and mode, T_{qgijm}, and their costs, c_{ijm}, depend on car ownership levels as do the costs of garages, p_i. Therefore, at first a rough approximation of trip expenditures is used to estimate initial car ownership, travel budgets and trip cost standards, and the submodel is reiterated together with the traffic assignment iterations.

Electric cars

Modelling electro mobility aims at assessing the diffusion of electric cars through possible technological developments and subsidy programmes and their impact on energy consumption and CO_2 emissions of transport. The simulation of the growing diffusion of electric cars in each zone is performed in the car availability part of the *Transport Submodel*. In that submodel the number of cars per household of each income group in each zone is assessed as a function of their monthly transport budget, the expected travel expenditures and the life-cycle cost of maintaining and parking a car in that zone per month. This corresponds to the assumption that households have to divide their transport budget between the expenditures for trips and vehicles (see Section 3.3).

In the car availability part of the *Transport Submodel* the share of electric cars is assessed by a logit model of the costs of owning and operating electric cars as compared with those of conventional cars in that zone (Huber and Schroedter, 2015):

$$C_{qi}^{e}(t,t+1) = [C_{qi}(t) - C_{qi}^{e}(t)]\, f\,(\underline{c}_i^{e} / \underline{c}_i) \tag{3.3}$$

where $C_{qi}^{e}(t,t+1)$ is the number of electric cars bought by households of income group q in zone i in period t, t+1 and $f\,(\underline{c}_i^{e} / \underline{c}_i)$ is a nonlinear function of the cost of owning and driving an electric car per month in that zone compared with that of a conventional car, including subsidies.

The availability of charging stations is taken account of by considering the costs of charging stations at origins and destinations of trips as part of the car operating costs. It is assumed that in low-density suburban areas charging takes place at home, so that no additional costs arise, and that in high-density inner-city areas, in order to promote electro mobility, a growing proportion of high-speed charging stations will have to be financed by public subsidies. This implies that the cost of owning and driving an electric car in inner-city areas consists of three components: the life-cycle cost of purchasing the car minus subsidies to promote electro mobility, the cost of parking the car either in a garage or on the street and the cost of using public charging stations in the street minus subsidies to finance them.

In the remaining *Transport Submodel* travel times and travel costs between zones are calculated as averages weighted by the shares of conventional and electric cars. This makes it possible to indicate for each road link the contribution of conventional and electric cars to energy consumption and CO_2 emissions.

Car-Sharing

There are two kinds of car-sharing: station-based and free-floating. Presently only free-floating car-sharing and how it affects car availability is addressed in the *Transport Submodel*. Because only little is known about the future market potential of car-sharing, the total number of car-sharing cars in the whole study region is exogenously assumed. However, the distribution of car-sharing cars in the zones of the region is endogenously modelled. It is assumed that free-floating car sharing is only possible in high-density residential areas because in low-density areas walking distances to the next available car would be too long. Therefore the exogenously assumed number of car-sharing cars is distributed across the zones via an exponential function of population density:

$$C_i^s = (P_i \ E_i) \ d_i^{1.5} \qquad \text{with} \qquad \sum_i C_i^s = \sigma \sum_i E_i \ 0.001 \tag{3.4}$$

where C_i^s is the number of car-sharing cars in zone $_i$, P_i and E_i are population and employment in zone i, respectively, and d_i is population density in zone i, and σ is the exogenous number of cars per 1,000 population.

In particular with free-floating car sharing two factors are at work: On the one hand there are car owners who sell their car and only occasionally use a car-sharing car. This reduces car availability. On the other hand there are mostly younger persons who so far have not bought a car but use the convenient possibility of car-sharing not requiring a large car purchasing investment. This increases car availability, in particular for younger households with lower incomes.

The question is which of these two influencing factors will have the larger impact – the answer to this question will decide whether car sharing will overall reduce or increase car availability and so whether car sharing can be considered as a policy to achieve the energy transition.

In the present version of the model car-sharing trips are generated by increasing and reducing car availability by exogenous proportions of the car-sharing cars in the zone. In addition trip utilities of trips by car-sharing cars might have been increased for households with lower income. This was not possible in the time available in the last project in which the model was used. Therefore, and because of lack of empirical data, a medium solution was chosen which results in slightly more abandoned car trips by former car drivers than induced car trips by former cyclists or pedestrians. These results need to be reinvestigated in future work.

(3) Network Analysis

The model uses two different minimum-path algorithms, one for the road network and one for the public transport network.

The minimum-path algorithm used for the road network determines the current minimum path between two zones i and j as a function of link travel times. On the first iteration of the transport equilibrium algorithm (see Network Equilibrium) network equilibrium travel times of the previous simulation period are used. In subsequent iterations link travel times calculated in the capacity-restraint step of the previous iteration of the algorithm are used.

The minimum-path algorithm used for the public transport network determines the minimum path between two zones i and j as a function of link travel times and waiting times at boarding and transfer stations. The algorithm automatically selects promising transfer connections at transfer stations as a function of headways of connecting lines, so no transfer connections need to be explicitly coded in the network. At each transfer station the algorithm decides whether to continue on the same line, change to another line or disembark (see Figure 3.2).

(4) Trip Utilities

Monetary and non-monetary costs and benefits of trips are aggregated by the model into one single measure called *trip utility*:

$$u_{qijm} = [\mathrm{v}_{tm} \ (t_{ijm})]^{w_{tq}} \ [\mathrm{v}_c \ (c_{ijm} \, / \, c_{oqi} \,)]^{w_{cq}} \ [v_{cf} \ cf_m]^{w_{cf}} \tag{3.5}$$

Here u_{qijm} is the utility of a trip from *i* to *j* using mode *m* for a household of type *q*; the w_{tq}, w_{cq} *and* w_{cf} are multiplicative importance weights adding up to one, and t_{ijm} and c_{ijm} are travel time and travel cost of the trip, respectively. Travel cost is seen in relation to c_{oqj} , the amount of money the household is willing and able to pay per trip, given its car ownership level and number of trips per month (see Equation 3.2).

These two monotone decreasing functions represent the only distance decay functions in the whole model. They are different for each mode to reflect characteristics of each mode not captured by the dimensions time and money. The weights w_{tq} and w_{cq}, however, are different for different household income groups to account for the different evaluation of time and money by people with different incomes. The cf_m is the comfort factor of mode *m*. The $v_{tm}(.)$, $v_c(.)$ and $v_{cf}(.)$ are value functions mapping travel time, cost and comfort to a common utility dimension.

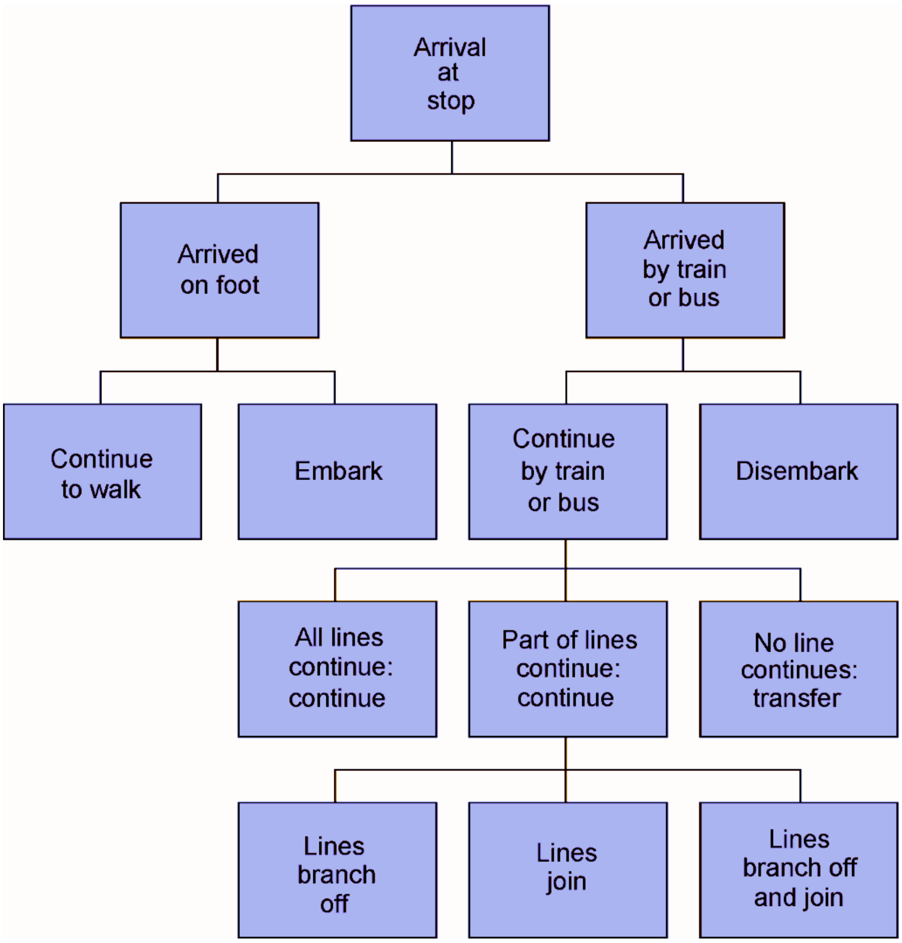

Figure 3.2. Options at transfer stops

(5) Trip Distribution

Another distinction between the sixteen travel demand models is related to constraints on destination choice. For work and school trips destinations are fixed, so doubly constrained models are appropriate. There are no constraints on destination choice for shopping and service/social trips, hence production-constrained models are used. Destination choice for work trips is performed only in the base year; in all subsequent years the work trip matrix is updated from moves in the *Housing Market Submodel*, and only modal choice is performed.

Destination and mode choice are combined into one integrated trip distribution model for each trip purpose and household income group. However, trip origins are split with respect to car availability. The following assumptions about car availability are made:

- All cars owned by a household are available for work trips.
    - Cars not used for work trips are available for shopping and service/social trips.
    - Cars not used for other trips are available for school trips by students with a driving licence.

With these assumptions, the combined destination and mode choice model is

$$t_{qgijm} = \sum_{k} A_{qgki} B_{qgj} O_{qgki}\, D_{qgj}\, \exp(\beta_g\, u_{qijm}) \tag{3.6}$$

where t_{qgijm} are trips made by household income group q for trip purpose g from i to j using mode m, O_{qgki} is the number of such trips originating in i with car availability k (k = 1: car available, k = 2: no car available), and D_{qgj} are trip destinations for that kind of trips in zones j. The u_{qijm} are the trip utilities calculated in Equation 3.5.

A_{qgki} and B_{qgi} are balancing factors ensuring that the origin and destination constraints, where applicable, are satisfied:

$$A_{qgki} = 1 / \sum_{j,m \in \mathrm{M}_k} B_{qgi} D_{qgj}\, \exp\,(\beta_g\, u_{qijm}) \tag{3.7}$$

$$B_{qgj} = \begin{cases} 1 / \sum\limits_{ik,m \in \mathrm{M}_k} A_{qgki}\, O_{qgki}\, \exp(\beta_g\, u_{qijm}) & \text{for } g = 1, 4 \\ 1 & \text{for } g = 2, 3 \end{cases} \tag{3.8}$$

where M_k is the subset of modes accessible with car availability k. For the eight doubly constrained models (g = 1, 4), the balancing factors are determined using iterative proportional fitting.

(6) Mode Choice

As an alternative to this one-parameter model, different parameters may be used for destination and mode choice. In that case the impedance term in Equations 3.6 to 3.8 is replaced by

$$\sum_{m \in M_k} \exp(\beta_g \, u_{qijm}) \frac{\exp(\lambda_g \, u_{qijm})}{\sum_{m \in M_k} \exp(\lambda_g \, u_{qijm})} \tag{3.9}$$

satisfying the modal share equation

$$p_{m|qgkij} = \frac{\exp(\lambda_g \, u_{qijm})}{\sum_{m \in M_k} \exp(\lambda_g \, u_{qijm})} \tag{3.10}$$

(7) Trip Assignment

In the trip assignment step, trips are assigned to links ℓ of network m such that the flow volume $v_{m\ell}$ of link ℓ in network m is

$$v_{m\ell} = \sum_{qgij} \delta_{ijm\ell} \, t_{qgijm} \tag{3.11}$$

where

$$\delta_{ijm\ell} = \begin{cases} 1 & \text{if } \ell \in r_{ijm} \\ 0 & \text{otherwise} \end{cases} \tag{3.12}$$

and $r_{ijm} = \{\ell_1, \ell_2, \ldots, \ell_R\}$ is the current minimum path in network m from i to j.

(8) Capacity Restraint

In the capacity restraint step, road network link travel times that correspond to link flow volumes $v_{m\ell}$ are calculated. A speed-flow relationship is used to adjust link travel times of congested road links:

$$t_\ell = t_{o\ell} \left[1 + \rho \left(\frac{v_\ell}{q_\ell \; h_p \; o_c} \right)^{\varphi} \right] \tag{3.13}$$

In this equation, t_ℓ is the adjusted and $t_{0\ell}$ the uncongested travel time on link ℓ, v_ℓ is the volume of car trips on that link during the peak period, and q_ℓ its capacity per hour, and h_p is the length of the peak period in hours and o_c the average car occupancy.

3.4 Network Equilibrium

User-optimum, congestion-sensitive equilibrium of car availability, trip generation and destination and mode choice is approached by applying an extended version of the network equilibrium algorithm by Evans (1976). For the one-parameter model specified in equations 3.6 to 3.8, the extended algorithm proceeds as follows:

(1) Calculate origin and destination activities.

(2) Make initial estimates of car ownership, trip cost standards, and trip rates.

(3) Find minimum public transport paths and calculate trip utilities for public transport and walking.

(4) Set iteration counter n to zero.

(5) Set n to n+1.

(6) Find minimum paths and calculate trip utilities for car trips.

(7) Solve the sixteen trip distribution models.

(8) Recalculate car ownership, trip cost standards and trip rates. If changes are large, go to (7).

(9) Assign car trips of (7) to minimum paths of (6) and calculate new link times and trip utilities.

(10) If n = 1 go to (5).

(11) Perform line search to find a value θ, $0 < \theta < 1$, maximising the objective function

$$\max_{\theta(n)} \; U[\mathrm{t}(n'),\mathrm{u}(n')] = \sum_{qgijm} t_{qgijm}(n')\, u_{qijm}(n') - \sum_{qg} \frac{1}{\beta_g} \sum_{ijm} t_{qgijm}(n') \, \ln t_{qgijm}(n') \tag{3.14}$$

where

$$t_{qgijm}(n') = [1-\theta(n)]\, t_{qgijm}(n-1) + \theta(n)\, t_{qgijm}(n) \tag{3.15}$$

and

$$u_{qijm}(n') = [1-\theta(n)]\, u_{qijm}(n-1) + \theta(n)\, u_{qijm}(n) \tag{3.16}$$

(12) Replace $\mathbf{t}(n)$ by $\mathbf{t}(n')$ and $\mathbf{u}(n)$ by $\mathbf{u}(n')$.

(13) If change of $U(n)$ over $U(n$-1) is large go to (5).

(14) Stop.

A good approximation of θ to avoid the line search is $\theta = 1/n$, i.e. giving equal weights to all successive solutions using the method of successive averages (Powell and Sheffi, 1982; Wegener, 1986). After about four iterations, changes of the convergence criterion as well as of car ownership, trip rates, destination and mode choice tend to be sufficiently small for this kind of analysis.

4. Ageing Submodel

In the *Ageing Submodel* all changes of zonal stock variables are modelled which are assumed to result from biological, technological or long-term socio-economic trends or originating outside of the model, i.e. which are not treated as *decision-based*. These changes are effected by probabilistic ageing or updating, or semi-Markov, models with dynamic transition rates. There are three such models for employment, population and households and housing.

4.1 Change of Employment

Change of zonal employment occurs in the model in three different submodels:

(1) Decline of zonal employment due to sectoral decline, lack of building space and intraregional relocation of firms is modelled in this submodel.

(2) Changes of zonal employment due to the location or removal of large plants exogenously specified by the user are executed in the *Public Programmes Submodel*.

(3) Changes of zonal employment due to new jobs in vacant industrial or commercial buildings, in newly built industrial or commercial buildings or in converted residential buildings are modelled in the *Private Construction Submodel*.

In the *Ageing Submodel* decline of zonal employment due to sectoral decline, lack of building space and intraregional relocation of firms is modelled. Each of the forty industries of the model is considered a separate submarket. The model starts from existing employment $E_{slj}(t)$ of industry s situated on land use category l in zone j at time t. There are three different ways for E_{slj} to change in this submodel:

a) Sectoral Decline

Declining industries make workers redundant. This occurs not necessarily at the same rate all over the region, but is more likely where locational conditions are less favourable:

$$R_{slj}(t,t+1) = \frac{E_{slj}(t)\exp[-\alpha_s\ u_{slj}(t)]}{\sum_{jl} E_{slj}(t)\exp[-\alpha_s\ u_{slj}(t)]}\ [E_s(t+1) - E_s(t)] \tag{4.1}$$

is the number of workers in industry s made redundant on land use category l in zone j between t and t+1. $E_s(t)$ indicates total employment of industry s in the region and $E_s(t+1)$ is the exogenous projection of total regional employment for time t+1. The utility $u_{slj}(t)$ expresses the attractiveness of land use category l in zone j for industry s (see below). R_{slj} is set to zero for growing industries.

b) Relocation

Some industries are very stationary, while others easily move from one location to another. If $r_s(t,t+1)$ is a sectoral mobility rate, then

$$M_{slj}(t,t+1) = \frac{E_{slj}(t)\exp[-\alpha_s\ u_{slj}(t)]}{\sum_{jl} E_{slj}(t)\exp[-\alpha_s\ u_{slj}(t)]}\ r_s(t,t+1)\ E_s(t) \tag{4.2}$$

is the number of workplaces relocated from land use category *l* in zone *j* during the period. The mobility rate $r_s(t,t+1)$ is exogenous.

c) Lack of Building Space

In most industries, mechanisation and automation tend to increase the building floorspace per workplace. Accordingly, in each period, a number of jobs S_{slj} have to be relocated because of lack of space:

$$S_{slj}(t,t+1) = E_{slj}(t)\left[1-\frac{b_{sj}(t)}{b_{sj}(t+1)}\right] - R_{slj}(t,t+1) \tag{4.3}$$

where $b_{sj}(t+1)$ is the projected floorspace per workplace in industry *s* in zone *j* at time *t*+1, which will be always greater than or equal to its value at time *t*. Where redundancies exceed relocations due to lack of space, S_{slj} is set to zero.

For the workers made redundant, later new buildings will have to be provided in the *Public Programmes Submodel* or in the *Private Construction Submodel*. Where decline of employment is large, buildings remain vacant, but these may be reused by other industries later.

4.2 Change of Population

The population projection model predicts zonal population by age, sex and nationality exclusive of migration. Changes of zonal population by migration into, out of or within the region are modelled in the *Housing Market Submodel*.

Changes of population due to fertility and mortality are modelled by a cohort-survival model subject to exogenous forecasts of fertility and mortality rates. To reduce data requirements, a simplified version of the cohort-survival population projection model with five-year age groups is applied. The method starts by calculating survivors for each age group and sex:

$$P'_{asi}(t+1) = P_{asi}(t)\ [1-d_{asi'}(t,t+1)] \tag{4.4}$$

where $P'_{asi}(t+1)$ are surviving persons of age group *a* and sex *s* in zone *i* in year *t*+1, $P_{asi}(t)$ is population of age group *a* and sex *s* in year *t* and $d_{asi'}(t,t+1)$ is the average annual death rate of age group *a* and sex *s* between years *t* and *t*+1 in the group of zones *i'* to which zone *i* belongs.

Next it is calculated how many persons change from one age group to the next through ageing employing a smoothing algorithm:

$$g_{asi}(t,t+1) = 0.12\,P'_{asi}(t+1) + 0.08\,P'_{a+1si}(t+1) \qquad \text{for } a = 1, 9 \tag{4.5}$$

where $g_{asi}(t,t+1)$ is the number of persons of sex *s* changing from age group *a* to age group *a*+1 in region *r*. Surviving persons in year *t*+1 are then

$$P_{asi}(t+1) = P'_{asi}(t+1) + g_{a-1si}(t,t+1) - g_{asi}(t,t+1) \qquad \text{for } a = 2, 19 \tag{4.6}$$

with special cases

$$P_{20si}(t+1) = P'_{20si}(t+1) + g_{19si}(t,t+1) \tag{4.7}$$

and

$$P_{1si}(t+1) = P'_{1si}(t+1) + B_{si}(t,t+1) - g_{1si}(t,t+1) \tag{4.8}$$

where $B_{si}(t,t+1)$ are births of sex s in zone i between years t and $t+1$:

$$B_{si}(t,t+1) = \sum_{a=4}^{10} 0.5\,[P'_{a2i}(t+1) + P_{a2i}(t+1)]\;\; b_{asi'}(t,t+1)\;\; [1 - d_{0si'}(t,t+1)] \tag{4.9}$$

where $b_{asi'}(t,t+1)$ are average number of births of sex s by women of child-bearing five-year age groups a, a = 4,10 (15 to 49 years of age) in the group of zones i' to which zone i belongs between years t and $t+1$, and $d_{0si}(t,t+1)$ is the death rate during the first year of life of infants of sex s in that group of zones.

If the duration of the simulation period is more than one year, the population projection model is executed once in each year of the simulation period.

4.3 Change of Households and Housing

Households are represented in the model as a four-dimensional distribution classified by:

- nationality (native, foreign)
- age of head (16-29, 30-59, 60+)
- income/skill (low, medium, high, very high)
- size (1, 2, 3, 4, 5+ persons)

Similarly, housing of each zone is represented as a four-dimensional distribution of dwellings classified by

- type of building (single-family, multi-family)
- tenure (owner-occupied, rented, public)
- quality (very low, low, medium, high)
- size (1, 2, 3, 4, 5+ rooms)

All changes of households and housing during the simulation are computed for these 120 household types and 120 housing types. However, where households and housing are cross-classified together, these households and housing types are aggregated to H household and K housing types, with H and K not exceeding 30.

The cross-classification of households and housing is performed in the *occupancy* matrix. The occupancy **R** of a zone is an H x K matrix representing the association of households with dwellings in the zone. Each element R_{hk} of the matrix contains the number of households of type h, h = 1, ..., H, occupying a dwelling of type k, k = 1, ..., K, the total matrix contains all households occupying a dwelling or all dwellings occupied by a household.

In addition, there are for each zone three vectors representing households without a dwelling or dwellings without a household. **S** is an H x 1 vector of subtenant households, **V** is an 1 x K vector of vacant dwellings and **N** is an 1 x K vector of dwellings newly constructed in the previous period and released to the market now.

By incorporating the zonal dimension i, i = 1, ..., I, the matrix **R** becomes three-dimensional, and the vectors **S**, **V** and **N** become two-dimensional matrices. **R**, **S**, **V** and **N** are a complete representation of the household/housing system at the outset of the simulation period. All changes occurring to households and housing during the period can be represented by transitions into, within, or out of these four matrices.

Changes occurring to households and housing affect either households only, dwellings only, or both households and dwellings. Households come into existence, grow, get older, separate or merge, get more or less income, finally shrink and disappear. Dwellings are built, maintained or upgraded, or deteriorate and eventually are torn down. The association of households with dwellings changes through occupations and vacations, and this leads to changes of the composition and price of housing supply.

Two principal kinds of changes can be distinguished: changes that are decision-based and changes that are not. For instance, migration and housing investments are normally based on rational decisions and are therefore modelled in decision models. The ageing of households and dwellings, however, depends only on the course of time and can therefore be modelled by probabilistic transition rates. Other changes are in reality decision-based, such as changes of household status through births, marriage or divorce, but are modelled probabilistically as the motivations behind these changes are of no interest for the purpose of the model. Still other consequences are merely consequences of events occurring in other sectors of the model, e.g. changes of household income due to employment changes. A last category of changes are exogenous, i.e. directly specified by the user such as public housing programmes.

Following this classification, changes of households and housing are modelled in different submodels:

(1) Ageing of households and housing and other demographic changes of household status are modelled in this submodel (see Figure 4.1).

(2) Public housing programmes specified by the model user are executed in the *Public Programmes Submodel*.

(3) Private housing maintenance/upgrading and new construction investments and the resulting changes in housing and land prices are modelled in the *Private Construction Submodel*.

(4) Changes of household income induced by changes in employment status are modelled in the *Labour Market Submodel*.

(5) Changes of the association of households with housing and the resulting changes in housing prices are modelled in the *Housing Market Submodel*.

In the *Ageing Submodel* all changes of households and housing are modelled that in the model are treated as merely time-dependent. For households such changes include demographic changes of households status in the household's life cycle such as ageing and death as well as birth, marriage and divorce and all new or dissolved households resulting from these changes, plus changes of nationality. On the housing side they include deterioration by ageing (filtering down the quality scale) and eventually demolition.

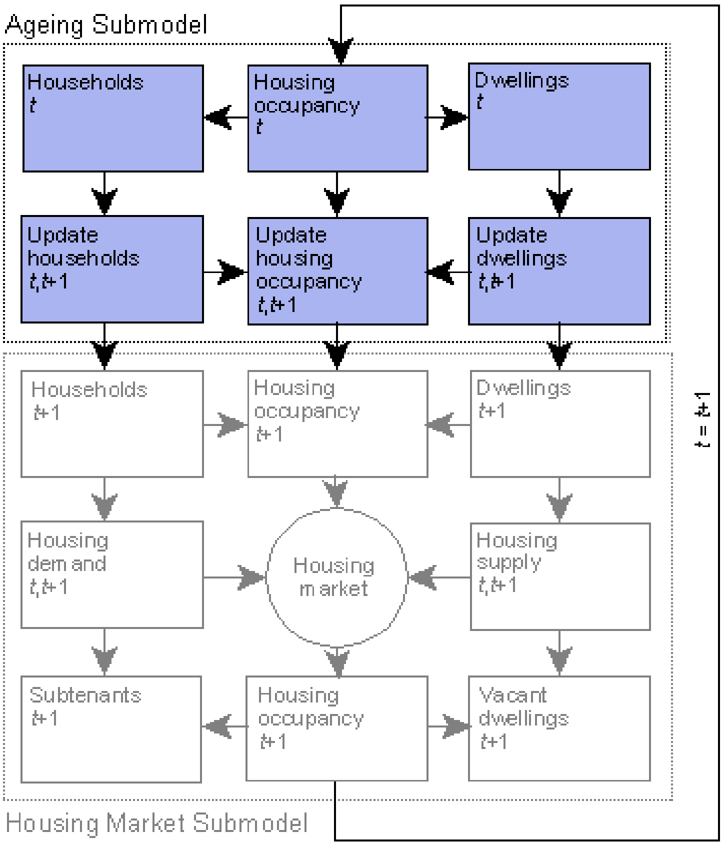

Figure 4.1. Changes of households and housing in the Ageing Submodel

Because of the association of households and housing in the occupancy matrix, households and housing are aged simultaneously in a common semi-Markov model with dynamic transition rates. A transition rate is defined as the probability that a household or a dwelling of a certain type changes to another type during the simulation period from time *t* to time *t*+1. The transition rates are computed as follows. The time-dependent changes to be simulated are interpreted as *events* occurring to a household or dwelling with a certain probability in time interval *t* to *t*+1. The *basic event probabilities* and their expected future development are determined exogenously or are taken from the demographic submodel (see Change of Population above). Eleven basic event probabilities were identified for each of the three household age groups:

1 change of nationality
2 ageing
3 marriage
4 birth, native
5 birth, foreign
6 relative joins household
7 death
8 death of child
9 marriage of child
10 new household of child
11 divorce

and two for the four housing quality groups:

1 deterioration
2 demolition

Not all household events occur to every household. Some are applicable only to singles, some only to families, some only to adults, some only to children. Some households events are followed by housing events, and vice versa: where a household dissolves, a dwelling is vacated and where an occupied dwelling is demolished, a household is left without a dwelling. The housing events contain only those changes of the housing stock which can be expected to occur under normal conditions in any housing area, i.e. a normal rate of deterioration and demolition. More demolition may occur in the *Private Construction Submodel*, where housing may have to make way for industrial or commercial land uses. Maintenance/upgrading and new housing construction are assumed to be demand-generated, i.e. decision-based, and are therefore treated in the *Private Construction Submodel*.

The basic event probabilities are aggregated to zone-specific transition rates between household or dwelling types in two matrices, $\mathbf{h}_i$ for households and $\mathbf{d}_i$ for dwellings using the disaggregate (120-type) household and housing distributions of each zone as weights. The matrices $\mathbf{h}_i$ and $\mathbf{d}_i$ are of dimensions H x H and K x K, respectively, where the rows indicate the source state and the columns the target state. Most events are independent of each other and can be aggregated multiplicatively; but some exclude others, i.e. are the complement to each other. Multiplication of $\mathbf{h}_i$ and $\mathbf{d}_i$ with the occupancy matrix $\mathbf{R}_i$ yields the occupancy matrix aged by one simulation period:

$$\mathrm{R}_i(t+1) = \mathrm{h}'_i(t,t+1)\ \mathrm{R}_i(t)\ \mathrm{d}_i(t,t+1) \tag{4.10}$$

where $\mathbf{h}'_i$ is the transpose of $\mathbf{h}_i$. This procedure assumes that all households of type h in zone i have the same transition rates no matter in which dwelling they live, and that all dwellings of type k in zone i have the same transition rates irrespective of their occupancy

Special provisions are necessary for events which create new households without a dwelling or vacant dwellings. New households without a dwelling are created by the events marriage of child, new household of child or divorce or by demolition of dwelling:

$$\Delta\mathrm{S}_i(t,t+1) = \mathrm{n}_i(t,t+1)\,\mathrm{R}_i(t) + \mathrm{n}_i(t,t+1)\,\mathrm{S}_i(t) + \mathrm{R}_i(t)\ \ \mathrm{q}_i(t,t+1) \tag{4.11}$$

where $\mathbf{n}_i(t,t+1)$ is an H x H matrix containing current household formation probabilities calculated from the above events and $\mathbf{q}_i$(t,t+1) is a K x 1 vector of demolition rates of housing types. An element $\mathbf{n}_{hh'i}(t,t+1)$ is defined as the probability that a new household of type h is produced by a household of type h' in zone i during the simulation period.

Similarly, vacant dwellings may be generated by dissolution of households:

$$\Delta\mathrm{V}_i(t,t+1) = \mathrm{r}_i(t,t+1)\ \mathrm{R}_i(t) \tag{4.12}$$

where $\mathbf{r}_i(t,t+1)$ is an 1 x H vector of household dissolution rates aggregated from events such as marriage, relative joins household and death. Of course, vacant dwellings may also result from housing construction, but this is modelled in the *Public Programmes Submodel* and *Private Construction Submodel* and becomes effective only in the following simulation period.

In addition is it necessary to age households and dwellings outside the occupancy matrix $\mathbf{R}$, as also households without dwelling get older:

$$\mathrm{S}_i(t+1) = \mathrm{h}_i(t,t+1)\ \ [\mathrm{S}_i(t) + \Delta\mathrm{S}_i(t,t+1)] \tag{4.13}$$

and also vacant dwellings deteriorate or may be torn down:

$$\mathrm{V}_i(t+1) = [\mathrm{V}_i(t) + \Delta\mathrm{V}_i(t,t+1) + \mathrm{N}_i(t-1,t)] \ \mathrm{d}_i(t,t+1) \tag{4.14}$$

where $\mathbf{N}_i(t{-}1,t)$ is the 1 x K vector of new dwellings constructed in the previous simulation period.

5. Public Programmes Submodel

Public programmes are events entered exogenously by the model user. They represent primarily public policy measures such as infrastructure investments or public housing programmes, where local, state or national governments directly intervene into the process of spatial urban development. In addition they represent "singular historical events" that are caused by private market decisions but are too unique and too large to be predicted by a model, such as the location or closure of large industrial plants, large commercial developments such shopping malls or large private housing developments. Public policy measures and large private projects in the above sense are entered by the model user.

Regulatory or monetary policies such as land use plans, building regulations, taxes, public transport fares or parking fees are not part of the *Public Programmes Submodel* but are entered exogenously by the model user.

In the *Public Programmes Submodel* three types of events are executed: changes of *employment*, changes of *housing* and changes of *infrastructure*.

5.1 Change of Employment

Exogenously specified changes of employment such as the location or closure of large industrial plants or large shopping malls are entered as a code specifying the kind of change (removal or location), the number and category (industry) of jobs to be removed or located and the year and zone in which this is to take place. In the case of removal, a distinction is made whether the associated buildings are to be torn down, too or are to remain vacant for later use by other industries. In the case of a new location also the industrial or commercial buildings required for the new facility are constructed. If there is not enough vacant industrial land in the zone, a limited percentage of housing of low quality, if available, may be torn down. If also this is not sufficient, the number of jobs to be located is reduced.

In addition, the impact of the removal or addition of employment on household incomes in the region is calculated using the method described in the *Labour Market Submodel*.

5.2 Change of Housing

Exogenously specified changes of housing, such as public housing programmes or large private housing developments, are entered as a code specifying the kind of change (removal, upgrading or location), the number and type of dwellings to be removed, upgraded or located and the year and zone in which this is to take place. In the case of removal and upgrading it is checked whether enough dwellings of the specified type are available to execute the policy. In the case of new construction, if there is not enough vacant residential land in the zone, a limited percentage of housing of low quality, if available, may be torn down. If also this is not sufficient, the number of dwellings to be built is reduced.

5.3 Change of Infrastructure

Exogenously specified changes of public infrastructure facilities are entered as a code specifying the kind of change (removal or location), the size and type of facility to be removed or located and the year and zone in which this is to take place. The following facilities are implemented (Table 4.1):

Table 5.1. Infrastructure facilities

Sector	Facility	Units
Social services	Senior citizens homes	Places
	Senior citizens clinics	Places
Health	Hospitals	Beds
Education	Kindergartens, 0-5 years	Places
	Kindergartens, 6-10 years	Places
	Elementary schools	Classes
	Secondary schools I	Classes
	Secondary schools II	Classes
	Secondary schools III	Classes
	Universities	Students
Culture*		
Recreation*		
Utilities*		
Transport	Parking	Cars
	Intercity trains	Departures/day
	ICE trains	Departures/day
	Motorway access	Exits

* not yet implemented

In the case of removal, it is checked whether enough facilities of the specified type are available to execute the policy. In the case of new construction, if there is not enough vacant suitable land in the zone, a limited percentage of housing of low quality, if available, may be torn down. If also this is not sufficient, the size of the facility to be built is reduced. For each new facility also the number of parking spaces required by the building code is provided.

6. Private Construction Submodel

The *Private Construction Submodel* considers investment and location decisions by private developers, i.e. by enterprises which erect new industrial or commercial buildings, and by residential developers who build flats or houses for sale or rent or for their own use. Thus the submodel is a model of the regional land and construction market.

6.1 Industrial Location

The industrial location submodel makes no distinction between basic and non-basic industries, i.e. all industries are located or relocated endogenously subject to sectoral employment projections for the whole region. The model locates industrial or commercial floorspace suitable as workplaces in the forty industries considered in the model. However, as the amount of floorspace occupied by worker is not constant over time and certain types of floorspace can be used by several industries, the model actually locates *workplaces* or employment, which are subsequently converted to floorspace. The location of workplaces of all industries may also be controlled exogenously by the user in the *Public Programmes Submodel* in order to reflect major events such as the location or closure of large plants in particular zones.

Change of zonal employment occurs in the model in four different submodels:

(1) Decline of zonal employment due to sectoral decline, lack of building space and intraregional relocation of firms is modelled in the *Ageing Submodel*.

(2) Changes of zonal employment due to the location or removal of large plants exogenously specified by the user are executed in the *Public Programmes Submodel*.

(3) Changes of zonal employment due to new jobs in vacant industrial or commercial buildings, in newly built industrial or commercial buildings or converted residential buildings are modelled in this submodel.

New workplaces are either located in existing vacant industrial or commercial buildings, in newly constructed industrial or commercial buildings or in converted residential buildings.

Before starting the location process, industries are sorted by decreasing floorspace productivity, or rent paying ability, and processed in that order.

The total demand for new workplaces of industry s in the region is

$$N_s(t,t+1) = E_s(t+1) - E_s(t) + \sum_{jl} \Delta E_{slj}(t,t+1) \tag{6.1}$$

where $\Delta E_{sli}(t,t{+}1)$ are net changes in employment of industry *s* on land use category *l* in zone *i* modelled in previous submodels resulting from sectoral decline, lack of building space and intraregional relocation of firms as well as from exogenously specified public programmes.

a) New Jobs in Vacant Buildings

Declining industries or relocating firms leave buildings vacant that may be used by other industries. For this purpose, the forty industries have been divided into groups with similar space requirements.

If this demand is less than the total supply of suitable floorspace, it is allocated to vacant floorspace with the following allocation function:

$$V_{slj}(t,t+1) = \frac{K_{slj} \exp[\gamma_s \, u_{slj}(t)]}{\sum_{jl} K_{slj} \exp[\gamma_s \, u_{slj}(t)]} N_s(t,t+1) \tag{6.2}$$

where K_{slj} is the capacity of existing buildings on land use category l in zone j for workplaces in industry s. V_{slj} is the number of jobs accommodated.

b) New Jobs in New Buildings

For any remaining demand, new industrial or commercial buildings have to be provided. This demand is allocated to vacant industrial or commercial land with the allocation function

$$C_{slj}(t,t+1) = \frac{L_{slj} \exp[\gamma_s \, u_{slj}(t)]}{\sum_{jl} L_{slj} \exp[\gamma_s \, u_{slj}(t)]} \left[N_s(t,t+1) - \sum_{jl} V_{slj}(t,t+1) \right] \tag{6.3}$$

where C_{slj} are new workplaces in industry s built on land use category l in zone j between t and t+1. L_{slj} is the current capacity of land of land use category l for such workplaces in zone i; since it is continuously reduced during the simulation period, it bears no time label.

The utility $u_{slj}(t)$ used in Equations 6.2 and 6.3 is the attractiveness of land use category l in zone j for industry s and has three components:

$$u_{slj}(t) = [u_{sj}(t)]^{v_s} \, [u_{sl}(t)]^{w_s} \, [\mathrm{u}_s(c_{lj})(t)]^{1-v_s-w_s} \tag{6.4}$$

where $u_{sj}(t)$ is the attractiveness of zone j as a location for industry s, $u_{sl}(t)$ is the attractiveness of land use category l for industry s, and $\mathrm{u}_s(c_{lj})$(t) is the attractiveness of the land price of land use category l in zone j in relation to the expected profit of economic activity s. The v_s, w_s, and $1–v_s–w_s$ are multiplicative importance weights adding up to unity. The three component utilities are constructed similarly to the components of the housing utility $u_{hki}(t)$ (see *Housing Market Submodel*). Like all utilities in the model, the $u_{slj}(t)$ remain unchanged during the simulation period as calculated at time t. The price or rent of industrial or commercial buildings is presently not represented in the model.

The land capacity L_{slj} is normally taken as being fixed as specified in the zoning plan. If a piece of land was formerly in a built-up area, its development implies the demolition of existing buildings. In addition, under certain restrictions in zones of high demand, the capacity L_{slj} may be extended by demolition of existing buildings with less profitable building uses to represent displacement processes going on within existing neighbourhoods. As L_{slj} is updated after the location of each industry, it bears no time label. All workplaces or dwellings displaced by demolition during a simulation period are replaced in the same period by iterating the industrial and residential submodels several times.

c) Conversion of Existing Dwellings

In the case of service workplaces, the capacity of a zone may also be extended by conversion of existing dwellings to offices where the demand for office space is high in relation to supply in order to represent the displacement of dwellings by offices observed within or near the CBD. All dwellings converted to offices during a simulation period are replaced in the same period by iterating the industrial and residential location submodels several times.

6.2 Retail Location

Retailing is treated like any other industry in the model except that the zonal attractiveness $u_{sj}(t)$ (see Equation 6.4) for retailing includes an attribute n

$$u_{sjn}(t) = \text{v}_n \left[\frac{\sum_{qim} t_{q2ijm}(t) \;\; y_{qi}(t) \,/\, E_{rj}(t)}{\sum_{hijm} t_{q2ijm}(t) \;\; y_{qi}(t) \,/\, E_r(t)} \right] \tag{6.5}$$

where $t_{q2ijm}(t)$ are shopping trips (g = 2) of households of income group q from residential zone i to shopping zone j using mode m, $y_{qi}(t)$ are retail expenses of households of income group q in zone i at time t, $E_{rs}(t)$ is retail employment in zone j at time t, $E_r(t)$ total regional retail employment, and $\text{v}_n(.)$ the value function mapping attribute n to utility. This attribute indicates retail sales per retail employee in zone j expressed in units of average turnover per retail employee in the whole region.

6.3 Housing Supply

Housing is represented in the model as a distribution of dwellings classified by (see *Housing Market Submodel*):

- type of building (single-family, multi-family)
- tenure (owner-occupied, rented, public)
- quality (very low, low, medium, high)
- size (1, 2, 3, 4, 5+ rooms)

This housing distribution is collapsed to up to thirty more aggregate housing types for use in the *occupancy matrix*, which links dwellings with households (see *Housing Market Submodel*). Changes to the housing stock in the zones occur in three submodels:

(1) Ageing of residential buildings, i.e. filtering down the quality scale, is modelled in the *Ageing Submodel*.

(2) Public housing programmes specified exogenously by the user are executed in the *Public Programmes Submodel*.

(3) Maintenance/Upgrading and new housing construction are modelled in the *Private Construction Submodel*.

Maintenance/Upgrading

Landlords are assumed to invest in their housing stock if by doing so they can expect to raise their profits. The proportion of dwellings upgraded in each period is calculated for each dwelling type in each zone as a function of the expected rent increase in that submarket after improvement. As the eventual rent increase is not known at this point in time, the landlords employ a simple rent expectation model based on vacancy rates at the beginning of the simulation period:

$$U_{ki}(t,t+1) = D_{ki}(t) \ \mathrm{f}\left[\frac{V_{ki}(t)}{D_{ki}(t)}\right] \tag{6.6}$$

where $U_{ki}(t,t+1)$ is the number of dwellings of housing type k in zone i to be upgraded if a sufficient number of dwellings of the same housing characteristics (size and building type) but lesser quality exits in the zone, $D_{ki}(t)$ is the number of dwellings of this type in the zone and $V_{ki}(t)$ is the number of vacant dwellings of this type. The exogenous elasticity curve f(.) controlling landlord investment behaviour specifies that landlords upgrade their stock if the number of vacancies is low.

Filtering and maintenance/upgrading work in opposite directions. Their net effect may result in an overall deterioration or improvement of the housing quality in a zone.

Energetic Retrofitting

With rising energy prices retrofitting of houses for saving energy has become an additional motivation.

In modelling the motivation of building owners to energy retrofit their buildings and their choice of energy efficiency to be achieved the payback period, i.e. the number of years after which the energy savings exceed the costs of the energy retrofitting proved to be an important variable (Fuerst and Wegener, 2013). Landlord behaviour is assumed to be demand-oriented. The willingness of landlords to invest in energy retrofitting depends on the probability of cost savings through improving the energy efficiency of buildings, such as better insulation or more efficient heating systems. The attractiveness of energy retrofitting can be measured by the payback period, i.e. the number of years needed until the accumulated discounted savings in building energy have become greater than the initial investment. The payback period P_{ki}(t) of dwellings of type k in zone i ends in year t if

$$C_{ki}(0) \ \leq \sum_t S_{ki}(t) \ / \ (1+r)^t \tag{6.7}$$

where $C_{ki}(0)$ is the initial cost minus any subsidies, r is the interest rate if the money were invested elsewhere and $S_{ki}(t)$ are the savings in energy made in each year until year t or, in the case of rented dwellings, the proportion of savings that can be recovered from tenants. It is assumed that investment in energy retrofitting is lower if the payback period is longer and higher if the payback period is shorter:

$$R_{ki}(t,t+1) = \mathrm{f}'\left[P_{ki}(t)\right] \tag{6.8}$$

where $R_{ki}(t,t+1)$ is the share of retrofitted buildings of type k in zone I in period t,t+t.

A last choice to be made is the degree of energy efficiency selected for the energy retrofitting. It is again assumed that this depends on the payback period:

$$e_{ki}(t,t+1) = \mathrm{f}''\left[P_{ki}(t)\right] \tag{6.9}$$

where $e_{ki}(t,t+1)$ is the energy efficiency of the building after the improvement expressed in percent of the full energy efficiency standard for residential buildings valid in period t,t+1. If the payback period is short, landlords are more likely to invest in full-scale energy efficiency.

New Housing Construction

The submarkets of the housing construction submodel are the housing types of the aggregate (30-type) housing classification, or rather a subset of them, as only good quality housing is assumed to be built.

Before starting the location process, housing types are sorted by decreasing price or rent per square metre and processed in that order.

The demand for new housing of type k to be built during the period from t to t+1, D_{kli}, is estimated by the model using a similar rent expectation model as in the maintenance/upgrading submodel:

$$C_k(t,t+1) = D_k(t)\ \mathrm{f}\left[\frac{V_k(t)}{D_k(t)}\right] \tag{6.10}$$

where $C_k(t,t+1)$ is the number of dwellings of housing type k to be built between times t and t+1. The difference to Equation 6.6 is that the estimated demand is totalled over all zones, as the location of new housing has yet to be determined.

The housing demand thus estimated is allocated to vacant residential land by a multinomial logit model:

$$C_{kli}(t,t+1) = \frac{L_{kli}\ \exp[\gamma_k\ u_{kli}(t)]}{\sum_{il} L_{kli}\ \exp[\gamma_k\ u_{kli}(t)]}\ C_k(t,t+1) \tag{6.11}$$

where $C_{kli}(t,t+1)$ are new dwellings of type k built on land use category l in zone i between t and t+1 and L_{kli} is the capacity of that vacant land for dwellings of type k. L_{kli} bears no time label as it is successively reduced during the simulation period by land uses with similar land requirements. The utility $u_{kli}(t)$ expresses the attractiveness of land use category l in zone i for dwellings of housing type k:

$$u_{kli}(t) = [u_{ki}(t)]^{v_k}\,[u_{kl}(t)]^{w_k}\,[\mathrm{u}(c_{kli})(t)]^{1-v_k-w_k} \tag{6.12}$$

where $u_{ki}(t)$ is the attractiveness of zone i as a location for housing type k, $u_{kl}(t)$ is the attractiveness of land use-category l for housing type k, and $\mathrm{u}(c_{kli})(t)$ is the attractiveness of the land price of land use category l in zone i in relation to the expected rent or price of the dwelling. The v_k, w_k and $1-v_k-w_k$ are multiplicative weights adding up to unity. The component utilities are constructed similarly to the components of the housing utility $u_{hki}(t)$ (see *Housing Market Submodel*). Like all utilities used in the model, the $u_{kli}(t)$ remain unchanged during the simulation period as calculated at time t.

Dwellings built during a simulation period utilise land immediately, but become available to the housing market only in the subsequent period.

6.4 Price Adjustment

At the end of each simulation period housing prices and rents are adjusted to reflect changes in the composition of the housing stock. Upgraded and new dwellings are more expensive than existing ones, so dwellings of a certain housing type become more expensive in zones with much building activity than in zones with little new housing construction.

Changes of housing prices and rents due to changes in demand are dealt with in the *Housing Market Submodel*, price increases through inflation in the *Ageing Submodel*. Prices or rents of industrial and commercial floorspace are presently not considered in the model.

Zonal land prices by land use category are adjusted as a function of the demand for land of that land use category in the zone in the period just completed, i.e. by the proportion of newly developed land of that category in the zone:

$$p_{lj}(t+1) = p_{lj}(t) \left[1 + \mathrm{f}\left(\frac{\Delta L_{lj}(t,t+1)}{L_{lj}(t)} \right) \right] \tag{6.13}$$

where $p_{lj}(t)$ is land price per square metre of land use category l in zone j at time t, ΔL_{lj}(t,t+1) is the amount of land of category j newly developed in zone l, and $L_{lj}(t)$ is the amount of developable land of that land use category in zone j at time t. The function f(.) is an S-shaped elasticity curve entered exogenously resulting in a reduction of land prices if no development took place in the period and a price increase if the rate of development was high. In built-up inner-city zones with little or no developable land a similar function of the proportion of redevelopment is used. No attempt is made to determine equilibrium land prices. The price adjustment model reflects price adjustment behaviour by land owners. If they decrease or increase prices too much, this will become apparent and be corrected in the subsequent simulation period.

7. Labour Market Submodel

The urban economy is represented in the model by employment (workers at place of work) and industrial and commercial buildings classified by forty industries. Labour force is represented by workers and unemployed persons at place of residence classified by four skill levels and by sex and nationality (native or foreign). The four skill levels correspond to the four income levels of the classification of households (see *Ageing Submodel* and *Private Construction Submodel*). There is no distinction between employed and self-employed persons. The distribution of skill levels of workers by industry is assumed to change over time according to exogenous assumptions.

There is no labour market in the strict sense in the model. Wage levels are assumed not to vary between different parts of the urban region nor between different group of workers of the same skill level and are therefore not considered. The labour market is assumed to be demand-driven; firms employ and release workers according to their needs, and this influences the distribution of employment, labour, unemployment and household incomes in the region.

7.1 Change of Employment

Change of zonal employment is not modelled in this submodel but in three other submodels:

(1) Decline of zonal employment due to sectoral decline, lack of building space and intraregional relocation of firms is modelled in the *Ageing Submodel*.

(2) Change of zonal employment due to the location or removal of large plants exogenously specified by the user is executed in the *Public Programmes Submodel*.

(3) Change of zonal employment due to new jobs in vacant industrial or commercial buildings or new construction of industrial or commercial buildings is modelled in the *Private Construction Submodel*.

7.2 Labour Mobility

For a variety of reasons workers change their workplace. If both workplace and residence are in the region, this does not normally imply a change of residence so that neither the distribution of workplaces nor the distribution of residences is changed. However, the pattern of work trips in the region is changed.

As nothing is known about work-related reasons of intraregional labour mobility, only reasons related to the work trip are modelled. It is assumed that, everything else being equal, a job nearer to home is more preferable than one farther away, so that the propensity to change job is inversely related to the trip utility of the work trip:

$$M_{qj}(t,t+1) = \sum_i \frac{t_{q1ij}(t)\ \exp[-\alpha\ u_{qij}(t)]}{\sum_{ij} t_{q1ij}(t)\ \exp[-\alpha\ u_{qij}(t)]}\ a_q(t,t+1)\ E_q(t) \tag{7.1}$$

where $M_{qj}(t,t+1)$ are workers of skill level q working in zone j considering a change of job between time t and time $t+1$, $t_{q1ij}(t)$ are work trips (g = 1) of workers of skill level (income group) q between residences in zones i and workplaces in zones j at time t and $u_{qij}(t)$ is the trip utility of work trips between zones i and j for workers of skill level q aggregated over modes:

$$u_{qij}(t) = \frac{1}{\lambda} \sum_{m \in M_h} \exp[\lambda \ u_{qijm}(t)] \tag{7.2}$$

The mobility rate $a_q(t,t+1)$ indicating how many workers of total workers $E_q(t)$ of skill level q are likely to change their jobs between t and t+1 is exogenous. It is assumed that when selecting a new job, again everything else being equal, also the distance between the old and the new job plays a role (see Figure 7.1).

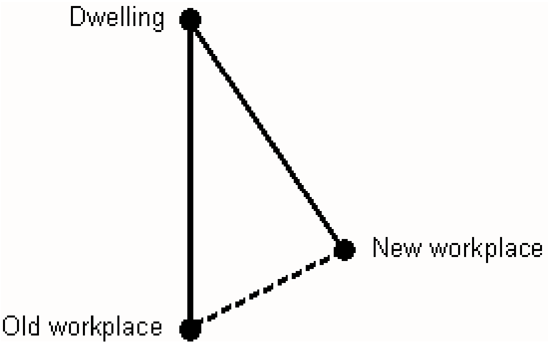

Figure 7.1 Change of job

Therefore a *change-of-job utility* similar to the migration utility used in the *Housing Market Submodel* is defined:

$$\underline{u}_{qjj'}(t) = u'_{qij'}(t)^{w_q} \ u_{qjj'm}(t)^{1-w_q} \tag{7.3}$$

with

$$u'_{qij'}(t) = \frac{1}{\beta} \ \ln \sum_i \frac{t_{q1ij}(t) \ \exp[\alpha \ u_{qij}(t)]}{\sum_i t_{q1ij}(t) \ \exp[\alpha \ u_{qij}(t)]} \ \exp[\beta \ u_{qij'}(t)] \tag{7.4}$$

The first part of the change-of-job utility (Equation 7.3) is the expected utility of a work trip from the old housing zone i to the new work zone j' after the move weighted by the probability that the worker lives in zone i (Equation 7.4), the second part evaluates the utility of a trip between the old and the new workplace. The w_q and $1–w_q$ are multiplicative weights adding up to unity.

With the above components a doubly constrained spatial interaction model is used to model job changes between work zones j:

$$M_{qjj'}(t,t+1) = M_{qj}(t,t+1) \ \ A_{qj} \ \ M_{qj'}(t,t+1) \ \ B_{qj'} \ \exp[\gamma \ \ \underline{u}_{qjj'}(t)] \tag{7.5}$$

where A_{qj} and $B_{qj'}$ are balancing factors.

7.3 Change of Income

Household incomes are classified into four household income groups (low, medium, high, very high) corresponding to the four skill levels of workers (see *Ageing Submodel*). It is assumed that all households within one of the four income groups have the same income irrespective of their location in the region. Household incomes also determine housing budgets (used in the *Housing Market Submodel* and travel budgets (used in the *Transport Submodel*) as well as disposable income for shopping (used in the retail location part of the *Private Construction Submodel*). Household incomes and housing, travel and shopping budgets of the four income groups are updated according to exogenously specified projections.

Changes of the income distribution of households are induced by changes of employment (see above). It is assumed that in the case of unemployment a household drops from one income group to the next lower one. Conversely, in the case of new employment the household is promoted by one income group. Changes of employment are calculated as redundancies or new jobs at places of work. It is assumed that workers are released or hired without regard of their place of residence. Therefore, using the work trip matrix (g = 1) calculated for each period in the *Transport Submodel*, changes of employment at places of residence can be inferred:

$$R'_{qi}(t,t+1) = \sum_j \frac{t_{q1ij}(t)}{\sum_{ij} t_{q1ij}(t)} \sum_s R_{sqj}(t,t+1) \tag{7.6}$$

$$N'_{qi}(t,t+1) = \sum_j \frac{t_{q1ij}(t)}{\sum_{ij} t_{q1ij}(t)} \sum_s N_{sqj}(t,t+1) \tag{7.7}$$

where $R'_{qi}(t,t+1)$ are workers made redundant and $N'_{qi}(t,t+1)$ newly employed workers of skill level q at places of residence i between time t and time t+1, $R_{sqi}(t,t+1)$ are workers of skill level q made redundant in industry s in work zones j in that period due to sectoral decline, lack of building space, intraregional relocation or exogenous user specification, and $N_{sqj}(t,t+1)$ are new jobs of skill level q created in industry s in work zone j in vacant or new buildings.

As the four worker skill levels correspond to the four household income groups, it is assumed that workers of skill level q belong to a household of the set of household types belonging to income group q. With this assumption, for each zone a 4 x 4 matrix of transition rates between household income groups is calculated and used for updating all household distributions including the occupancy matrix.

8. Housing Market Submodel

In the this submodel transactions on the regional housing market and the resulting changes in housing prices and rents are modelled.

Changes of households and housing are modelled in different submodels:

(1) Ageing of households and housing and other demographic changes of household status are modelled in the *Ageing Submodel*.

(2) Public housing programmes specified by the model user are executed in the *Public Programmes Submodel*.

(3) Private housing maintenance/upgrading and new construction investments and the resulting changes in housing and land prices are modelled in the *Private Construction Submodel*.

(4) Changes of household income induced by changes in employment status are modelled in the *Labour Market Submodel*.

(5) Changes of the association of households with housing and the resulting changes in housing prices are modelled in this submodel (see Figure 8.1).

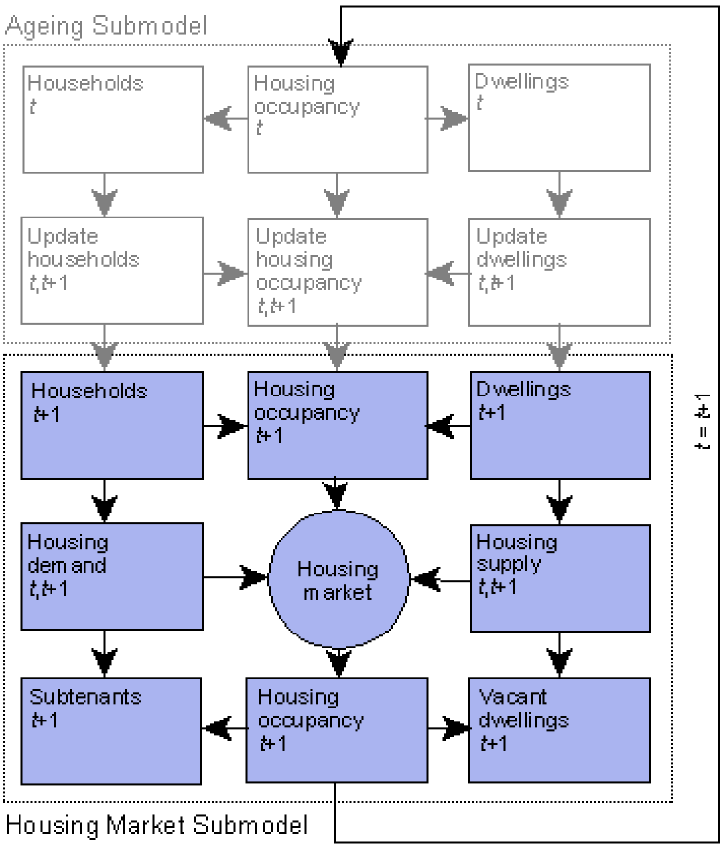

Figure 8.1. Changes of household and housing in the Housing Market Submodel

8.1 Household Moves

The *Housing Market Submodel* simulates intraregional migration decisions of households as search processes in the regional housing market. Thus it is at the same time an intraregional migration model. Housing search is modelled in a stochastic microsimulation framework. The results of the *Housing Market Submodel* are intraregional migration flows by household category between housing by category in the zones.

Households are represented in the model as a four-dimensional distribution classified by nationality (native, foreign), age of head (16-29, 30-59, 60+), income/skill (low, medium, high, very high) and size (1, 2, 3, 4, 5+ persons). Similarly, housing of each zone is represented as a four-dimensional distribution of dwellings classified by type of building (single-family, multi-family), tenure (owner-occupied, rented, public), quality (very low, low, medium, high) and size (1, 2, 3, 4, 5+ rooms). All changes of households and housing during the simulation are computed for these 120 household types and 120 housing types. However, where households and housing are cross-classified together, these households and housing types are aggregated to *H* household and *K* housing types, with *H* and *K* not exceeding 30 (see *Ageing Submodel*).

Technically, the migration submodel is a Monte Carlo micro simulation of a sample of representative housing market *transactions*. However, it differs from other, 'list-oriented', micro simulations in that (a) sampling and aggregation are part of the simulation and (b) stocks (households and dwellings) are classified, i.e. aggregate, data. A market transaction is any successfully completed operation by which a migration occurs, i.e. a household moves into or out of a dwelling or both. A market transaction has a *sampling phase*, a *search phase*, a *choice phase* and an *aggregation phase* (Wegener, 1986; Wegener and Spiekermann, 1996):

- In the *sampling phase* a household looking for a dwelling or a landlord looking for a tenant is sampled for being simulated.
- In the *search phase* the household looks for a suitable dwelling, or the landlord looks for a tenant.
- In the *choice phase* the household decides whether to accept the dwelling or not.
- In the *aggregation phase* all changes of households and dwellings resulting from the transaction, multiplied by the sampling factor, are performed.

The sampling phase and the search phase are controlled by multinomial logit choice functions. For instance, for a household looking for a dwelling,

$$p_{k|hi} = \frac{R_{hki}\ \exp[-\alpha_h\ u_{hki}(t)]}{\sum_k R_{hki}\ \exp[-\alpha_h\ u_{hki}(t)]} \tag{8.1}$$

is the probability that of all households of type h living in zone i, one occupying a dwelling of type k will be sampled for simulation,

$$p_{i'|hki} = \frac{\sum_{k'} D_{k'i'}\ \exp[\beta_h\ \underline{u}_{hii'}(t)]}{\sum_{i'k'} D_{k'i'}\ \exp[\beta_h\ \underline{u}_{hii'}(t)]} \tag{8.2}$$

is the probability that the household searches in zone i' for a new dwelling and

$$p_{k'|hki'} = \frac{D_{k'i'} \exp[\gamma_h \, u_{hk'i'}(t)]}{\sum_{k'} D_{k'i'} \exp[\gamma_h \, u_{hk'i'}(t)]} \tag{8.3}$$

is the probability that it inspects a dwelling of type k' there before making a choice. In these equations R_{hki} is the number of households of type h living in a dwelling of type k in zone i, and $D_{k'i'}$ is the number of vacant dwellings of type k' in zone i'. The $u_{hki}(t)$ and the $\underline{u}_{hii'}(t)$ are two different kinds of utility measures expressing the attractiveness of a dwelling or a zone for a household considering a move. They are discussed in Equations 8.4 and 8.9. The two utilities carry the time label t, i.e. are unchanged since the beginning of the simulation period, while R_{hki} and $D_{k'i'}$ carry no time label as they are continuously updated during the microsimulation.

In the choice phase, the household decides whether to accept the inspected dwelling or not. It is assumed that it behaves as a satisficer, i.e. that it accepts the dwelling if this will improve its housing situation by a considerable margin. Otherwise, it enters another search phase to find a dwelling, but after a number of unsuccessful attempts it abandons the idea of a move. The amount of improvement necessary to make a household move is assumed to depend on its prior search experience, i.e. go up with each successful and down with each unsuccessful search. In other words, households are assumed to adapt their aspiration levels to supply conditions on the market.

The results of the migration submodel are intraregional migration flows of households (including starter households and inmigrant and outmigrant households) by household type between dwellings by type in the zone.

The attractiveness of a dwelling of type k in zone i for a household of type h, $u_{hki}(t)$, is a weighted aggregate of housing attributes:

$$u_{hki}(t) = [u_{hi}(t)]^{v_h} \, [u_{hk}(t)]^{w_h} \, [\mathrm{u}_{q(h)h}(c_{ki})(t)]^{1-v_h-w_h} \tag{8.4}$$

where $u_{hi}(t)$ is the attractiveness of zone i as a housing location for household type h, $u_{hk}(t)$ is the attractiveness of housing type k for household type h, and $\mathrm{u}_{q(h)}(c_{ki})$ is the attractiveness of the rent or price of the dwelling in relation to the household's housing budget, which is a function of its income group $q(h)$. The v_h, w_h and $1-v_h-w_h$ are multiplicative importance weights adding up to unity.

Both $u_{hi}(t)$ and $u_{hk}(t)$ are themselves multiattribute encompassing relevant attributes of the neighbourhood:

$$u_{hi}(t) = \sum_n a_n \, \mathrm{v}_n \; \mathrm{f}_n[\mathrm{X}_i(t), \mathrm{U}_{q(h)i}(t)] \tag{8.5}$$

or of the dwelling:

$$u_{hk}(t) = \sum_n b_n \, \mathrm{w}_n \; \mathrm{g}_n[\mathrm{X}_k(t)] \tag{8.6}$$

where subscript n indicates attribute n. The a_n and b_n are importance weights adding up to unity, the $\mathrm{v}_n(.)$ and $w_n(.)$ are value functions mapping attributes to utility, and the $\mathrm{f}_n(.)$ and $\mathrm{g}_n(.)$ are generation functions specifying how to calculate attributes from one or more elements of vectors $\mathbf{X}_i(t)$ or $\mathbf{X}_k(t)$ of raw attributes of zone i or dwelling type k or vectors of accessibility indices $\mathbf{U}_{q(h)i}(t)$ of zone i (see below). The housing price attractiveness $\mathrm{u}_{q(h)}(c_{ki})$ is calculated as

$$\text{u}_{q(h)}(c_{ki}) = \text{u}_{q(h)}\,(c_{ki} \,/\, y_{q(h)k}) \tag{8.7}$$

where c_{ki} is rent, or imputed rent, of dwelling type k in zone i, and $y_{q(h)k}$ is the monthly housing budget of household type h belonging to income group q for this dwelling type. The housing budgets include housing allowances and other public subsidies and are therefore different for rented and owner-occupied dwellings.

The $\mathbf{U}_{q(h)i}(t)$ are household income-group specific vectors of accessibility indices describing the location of zone i in the region with respect to activities $W_{nj}(t)$ in zones j:

$$u_{qni}(t) = \sum_{j,m \in \text{M}q} \frac{W_{nj}(t)\ \exp[\beta_n\, u_{qijm}(t)]}{\sum\limits_{j,m \in \text{M}_q} W_{nj}(t)\ \exp[\beta_n\, u_{qijm}(t)]}\quad u_{qijm}(t) \tag{8.8}$$

The accessibility is expressed in terms of mean trip utility, i.e. as a weighted average of potential trips from zone i to activities or facilities $W_{nj}(t)$ of type n in zone j using mode m with trip utility $u_{qijm}(t)$ for household income group q (see *Transport Submodel* for a discussion of trip utilities). The set $\mathbf{M}_q$ includes all transport modes accessible to households of income group q depending on its car ownership level (see *Transport Submodel*).

The attractiveness measure $\underline{u}_{hii'}(t)$ used in Equation 8.2 is a relational utility describing the attractiveness of a zone i' as a new housing location for a household of type q now living in zone i and working in any of the zones near i (see Figure 8.2).

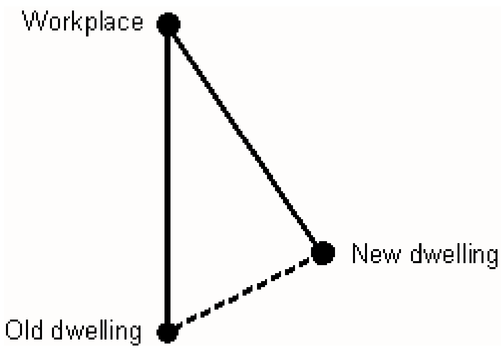

Figure 8.2 Change of residence

Hence it is called *migration utility*:

$$\underline{u}_{hii'}(t) = u'_{hi'j}(t)^{w_q}\ u_{q(h)hii'}(t)^{1-w_q} \tag{8.9}$$

with

$$u'_{hi'j}(t) = \frac{1}{\beta}\ \ln \sum_j \frac{t_{q(h)1ij}(t)\ \exp[\alpha\ u_{q(h)ij}(t)]}{\sum\limits_j t_{q(h)1ij}(t)\ \exp[\alpha\ u_{q(h)ij}(t)]}\ \exp[\beta\ u_{q(h)i'j}(t)] \tag{8.10}$$

and

$$u_{q(h)ij}(t) = \frac{1}{\lambda} \sum_{m \in \mathrm{M}_h} \exp[\lambda \ u_{q(h)ijm}(t)] \tag{8.11}$$

The first part of the migration utility (Equation 8.9) is the expected utility of a work trip from the new housing zone *i'* to work zone *j* after the move weighted by the probability that the household works in *j* (Equation 8.10) aggregated across modes (Equation 8.11), the second part evaluates the utility of a trip between the old and the new housing zone. The w_q and $1-w_q$ are multiplicative weights adding up to unity.

8.2 Price Adjustment

At the end of each simulation period housing prices and rents are adjusted to reflect changes in housing demand in the previous housing market simulation. Changes of housing prices and rents due to changes in the composition of the housing stock are dealt with in the *Private Construction Submodel*, price increases through inflation in the *Ageing Submodel.*

Housing prices and rents by housing type and zone are adjusted as a function of the demand for housing in that submarket in the period expressed by the proportion of vacant units:

$$p_{ki}(t+1) = p_{ki}(t) \left[1 + \mathrm{f} \left(\frac{V_{ki}(t+1)}{D_{ki}(t+1)} \right) \right] \tag{8.12}$$

where $p_{ki}(t)$ is monthly rent or imputed rent per square metre of housing floorspace of dwelling type *k* in zone *i* at time *t*, V_{ki}(t+1) is the number of vacant dwellings of housing type *k* in zone *i* at time t+1, and $D_{ki}(t)$ is the total number of dwellings of that type in the zone at time t+1. The function f(.) is an inverted S-shaped elasticity curve entered exogenously resulting in a reduction of housing prices and rents if there is a large percentage of vacant dwellings of that kind not bought or rented in the previous housing market simulation, and in a price or rent increase if there are no or only few vacant dwellings left. No attempt is made to determine equilibrium housing prices or rents. The price adjustment model reflects price adjustment behaviour by landlords. If they reduce or increase prices or rents too much, this will be corrected in the subsequent simulation period.

9. Model Data

The data required for the IRPUD model can be divided into four groups: *model parameters*, *regional data*, *zonal data* and *network data*:

Model Parameters

Model parameters are defined as all model input data required to specify the level and shape of model equations. Model parameters can be classified into seven groups:

(1) *Demographic parameters*. The demographic parameters essentially consist of survival and birth rates needed for the projection of population development in each zone in the *Ageing Submodel* disaggregated by age, sex and nationality and forecast separately for each category.

(2) *Household parameters*. The household formation model in the *Ageing Submodel* is based on probabilities for events affecting the composition and number of households, such as marriage, divorce, separation of children from their parents, joining of relatives, etc. In addition, the demographic parameters apply also to household members. The event probabilities are forecast for each household age group.

(3) *Housing parameters*. These parameters control the ageing of the housing stock in the *Ageing Submodel*, i.e. changes which are only time-dependent. Demand-generated changes to the housing stock such as new construction and modernisation are forecast in the *Private Construction Submodel*.

(4) *Technical parameters*. The technical parameters include land use parameters such as the relationship between gross and net floorspace, the land requirements of roads and public facilities and regulations on the provision of parking space, as well as transport parameters such as road capacity by road type and petrol consumption per car-kilometre.

(5) *Monetary parameters*. A large part of the model parameters are monetary parameters. *Income parameters* comprise all parameters necessary to determine the expendable income of households in terms of separate household *budgets* for *housing*, *transport* and *other purposes and savings* by household income group. For the housing budget, also housing subsidies such as housing allowances, tax benefits, savings bonuses, direct subsidies and loans with their respective regulatory framework are entered. *Cost parameters* encompass all information needed to determine prices in the housing and transport markets such as housing construction, modernisation and maintenance costs and the costs of petrol, car ownership, parking fees and public transport fares. During model execution, all monetary parameters are inflated by their appropriate inflation rate to yield current budgets and prices for each point in time; in addition most prices are adjusted up or down in response to local demand and supply conditions.

(6) *Preference parameters*. The preference parameters are the parameters of the multi-attribute attractiveness functions of the model. Six different kinds of attractiveness indicators are calculated for sites and dwellings:

(7) *Transport parameters*. The *Transport Submodel* requires transport-related parameters such as mean travel expenditures per household by income group (time series), consumer price index (time series), public transport fares, paring costs, petrol prices, costs of owning a car, and price elasticities of travel budgets, functions to estimate travel times of connector links and walking and cycling trips, parking search times, capacity restraint and fuel consumption, as well as initial trip rates by trip purpose, car occupancy and average parking time and the proportion of holders of driving licenses.

Regional Data

As the model is concerned with *intraregional* change processes, it requires information on the overall economic and demographic development of the total urban region:

- employment: industries (40)
- immigration: nationality(2), sex(2), age(30)
- outmigration: nationality(2), sex(2), age(30)

Alternatively , the regional control totals can be derived from the results of the SASI regional economic model (http://www.spiekermann-wegener.de/mod/sasimod.htm) to link the model to national or European policies. There exists an interface between the SASI and IRPUD models.

Zonal data

The zonal data describe the distribution of urban stocks and activities in the urban region in the base year of the simulation. For each zone the following data are required:

- population: nationality (2), sex (2), age (20)
- labour force/unemployed: nationality (2), sex (2), skill/income (4)
- households: nationality (2), age of head (3), income (4), size (5)
- dwellings: type of building (2), tenure (3), quality (4), size (5)
- households/housing: households (30), dwellings (30), housing occupation (30x30)
- employment/workplaces: industries (40)
- public facilities: facility type (40)
- land use: land use/zoning type (30)
- rents/prices: dwelling types (30), land use/zoning types (10)

Network Data

The network information for the *Transport Submodel* is contained in a single network file containing both the past and the assumed future evolution of the relevant transport modes of the regional transport network. The network file consists of two parts, a *link* part and a *line* part:

- For each *link* the following information is coded on one or more records:
  - link type,
  - time label (year of completion),
  - direction (one-way, two-way),
  - from-node,
  - to-node,
  - link length,
  - link travel time (public transport),
  - base speed (road).
- For each public transport *line* the following information is coded:
  - list of nodes called,
  - peak-hour headway (by section if different).

The network analysis part of the *Transport Submodel* automatically separates the road network and the public transport network and synthetically generates a third network for walking and bicycle trips. Public transport lines are automatically assigned to the links of the network; the headways of lines using the same route are amalgamated to allow for synergies between lines. Transfer connections are not coded in the network file but automatically established during route-search taking account of transfer waiting times and the inconvenience of transfer. The zone centroids are connected to the three networks by non-physical pseudo or connector links.

The model user may specify any time-sequenced programme of additions, deletions or modifications of network links. Modifications may be changes of link type (e.g. number of lanes), of travel time (public transport), of base speed (road) or of public transport lines or headways. There may be several consecutive changes for one link; as each change is identified by a time label (year of completion), the model assembles the current state of the network for each point in time. Even the network for the base forecast is likely to contain numerous network changes reflecting the foreseeable network improvements already under way. It is also possible to generally decrease or increase *all* travel times road travel times or public transport travel times or headways.

10. Model Policies

The IRPUD model was designed to study the impacts of exogenous assumptions or policies from the fields of industrial development, housing, public facilities and transport. Exogenous inputs are forecasts of total regional employment and total immigration into and outmigration out of the region subject to long-term economic trends. Policies are public policies in the fields of economic development, land use, housing, public facilities or transport. There are two kinds of policies in the model: *global* and *local*.

Global policies affect the economic or institutional environment of urban development in the whole region:

- *Global economic policies*. National policies such as changes in tax laws or subsidisation policies are entered by making changes to the respective parameters. If it is assumed that such policies also affect the forecasts of employment and immigration and outmigration made for the total region, these may also be changed. One example would be the effects of a change in immigration policy on the inflow of foreign workers into the region.

- *Global housing policies*. National policies affecting taxation and subsidies in the housing sector or new or changed regulations governing land use or construction activity can be entered by changing the respective model parameters. Policies changing the volume and type of public housing construction or renewal may be entered either globally or locally targeted to specific zones.

- *Global transport policies*. Policies affecting the whole transport system may be changes in transport-related taxes or subsidies resulting in changes to petrol prices, parking fees or public transport fares. Other policies such as general speed limits or road pricing schemes addressing particular types of roads require changes to the network data.

Local policies may be either regulatory or direct investment projects. In either case they are zone-specific:

- *Local land use planning* is reflected in the model in the form of a land use or zoning plan for each zone. A land use or zoning plan is actually a special file containing permitted land use changes specified by origin-category and destination-category, area and year. An entry in the land use or zoning plan does not imply that the land use change specified will actually take place; however it *may* take place if there is sufficient demand for construction activity of the specified kind. Without specification in the land use or zoning plan, construction activity can only take place on vacant sites or after demolition of the existing buildings.

- *Local economic policies* may result in new industrial locations, relocations of firms, or plant closures. If the change involves only one or a few major employers of the region, the model cannot be expected to predict such decisions (even if they are made by private actors). In such a case the change of employment is coded just as a public policy in a particular zone in a particular year. In the case of a new industrial location, the model tries to find the necessary land in the zoning plan of the specified zone and constructs the specified work-places with buildings, access roads and parking. In the case of a plant closure, the vacant industrial land is either released for new construction or retained by the firm depending on the specification by the model user.

- *Local housing policies* may result in new housing projects or urban renewal projects in specific zones. These projects, too, can be phased in volume and composition of dwelling types over any time period. Housing projects may be publicly or privately financed; what matters is only that they are explicitly specified by the model user and not generated by investment decisions in the *Private*

Construction Submodel. With all housing projects, the model checks whether the necessary land is available in the land use or zoning plan and provides access roads and parking facilities. In addition policies to promote energy retrofitting of residential buildings through subsidies can be introduced.

- *Local public facilities*. The user may specify a wide range of public facilities to be constructed in particular zones and in particular years, such as schools, hospitals, recreation facilities etc. In each case the necessary land is obtained in the land use or zoning plan and the required access roads and parking facilities are built.

- *Local transport policies*. The model user can specify any time-sequenced programme of additions, deletions or modifications of network links. Modifications may be changes of link type (e.g. number of lanes), of travel time (public transport), of base speed (road) or of public transport lines or headways. There may be several changes for one link; as each change is identified by a time label (year of completion), the model is able to assemble the current state of the network for each point in time. In fact even the network for the base forecast contains numerous network changes reflecting the foreseeable network improvements already under way. In addition policies to promote new transport modes, such as electro mobility and car-sharing through subsidies can be entered.

11. Model Results

The model predicts for each simulation period intraregional location decisions of industry, residential developers and households, the resulting migration and travel patterns, construction activity and land use development and the impacts of public policies in the fields of industrial development, housing, public facilities and transport.

In all cases, the first simulation is the so-called *base forecast*, which is defined as the most likely development of the region if all trends in effect in the base year also prevail during the forecasting period. Sometimes the base forecast is also called the do-nothing alternative, but this is misleading as policies which are already in effect or which are 'in the pipeline', i.e. which are certain to become effective soon, are included in the base forecast.

The model generates extensive result files from which a broad spectrum of graphical and tabular output can be produced. Graphical output is in the form of trajectories or maps. Trajectories are curves representing the development of a particular model variable or output indicator over time. Trajectory diagrams contain either trajectories for different zones or subregions (groups of zones) or the total urban region or trajectories of different scenarios. There are four kinds of output indicators: zonal indicators, matrix indicators, link indicators and raster indicators.

Zonal Indicators

Zonal indicators refer to tones or aggregates of zones of the study area. To save disk space, the model produces for each scenario a compact result file with zonal indicators for each simulation period. There are 13 categories of zonal indicators. Table 11.1 lists the indicators associated with each indicator category.

Table 11.1 Zonal indicators

Fields	Indicators
Population	Population (1990=100) Percent foreign population Percent population 0-4 years Percent population 5-14 years Percent population 15-19 years Percent population 20-24 years Percent population 25-29 years Percent population 30-59 years Percent population 60+ years Mean age
Households	Households (1990=100) Mean household size Percent single households Percent large households (5+) Percent households with low income Percent household with high income Mean household income (Euro) Mean household housing cost (Euro)
Migration	Net migration population (% per year) Net migration population 0-14 years (% per year) Net migration population 15-29 years (% per year) Net migration population 60+ years (% per year) Net migration foreign population (% per year) Net migration households (% per year) Net migration households low income (% per year) Net migration households medium income (% per year) Net migration households high income (% per year)
Employment	Employment (1990=100) Employment (jobs/ha) Nonservice employment (jobs/ha) Retail employment (jobs/ha) Service employment (jobs/ha) Labour force participation (%) Job-labour ratio (%) Percent unemployment
Housing	Dwellings (1990=100) Percent single-family dwellings Floor space per capita (sqm) Residential rent (Euro/sqm/month) Percent subtenant households Percent vacant dwellings Percent new housing per year Percent housing demolition per year

Table 11.1 Zonal indicators (continued)

Fields	Indicators
Land use	Built-up land (1990=100) Population density (pop/ha) Net population density (pop/ha built-up land) Percent built-up land Percent change of built-up land Percent vacant residential land Percent vacant industrial land Land price, residential (Euro/sqm) Land price, industrial/commercial (Euro/sqm)
Accessibility	Accessibility of jobs (0-100) Accessibility of shops (0-100) Accessibility of services (0-100) Accessibility of high schools (0-100) Accessibility of population (0-100) Accessibility of retail purchasing power Accessibility of services purchasing power Accessibility of Intercity stations (0-100) Accessibility of motorway exits (0-100) Accessibility of CBD (0-100)
Attractiveness	Attractiveness for housing, single-family Attractiveness for housing, multi-family Attractiveness for industry Attractiveness for small industry and crafts Attractiveness for retail Attractiveness for services
Travel (trips)	Trips (1990=100) Percent car trips Percent public transport trips Percent bicycle trips Percent walking trips Mean travel time work trips (min) Mean trip length work trips (km) Mean travel cost work trips (Euro) Mean travel time (min) Mean trip length (km) Mean travel cost per trip (Euro)
Travel per capita	Trips per capita per day Travel time per capita per day (min) Travel distance per capita per day (km) Car-vehicle-km per capita per day Public transport cost per capita per month (Euro) Car fuel cost per capita per month (Euro) Parking charge per capita per month (Euro) Road charge per capita per month (Euro) Fixed car cost per capita per month (Euro) Cars per 1,000 population Car trip cost per capita per month (Euro) Car costs per capita per month (Euro) Transport cost per capita per month (Euro) Car-sharing cars per 1,000 population

Table 11.1 Zonal indicators (continued)

Fields	Indicators
Travel per household	Trips per household per day Travel time per household per day (min) Travel distance per household per day (km) Car-km per household per day Public transport costs per household per month (Euro) Car fuel cost per household per month (Euro) Parking charge per household per month (Euro) Road charge per household per month (Euro) Fixed car cost per household per month (Euro) Cars per household Car trip cost per household per month (Euro) Car cost per household per month (Euro) Transport cost per household per month (Euro) Cost of a garage per car per month (Euro) Transport cost per household per month (Euro) Transport budget per household per month (Euro)
Environment (land use)	Population (percent of total region) Workplaces (percent of total region) Percent built-up area Percent open space Energy use of residential buildings (MWh/capita/year)', Energy use of residential buildings (kWh/sqm/year)', CO_2 emission of residential buildings (t/capita/year)', CO_2 emission of residential buildings (kg/sqm/year)', Share of energy-efficient residential floorspace (%) CO_2 emissions of housing and transport (t/capita/year) Mean retrofitting payback period (years)
Environment (transport)	CO_2 emissions public transport per capita (t/year CO_2 emissions car per capita (t/year) CO_2 emissions transport per capita (t/year) Walking and cycling km per capita per day Public transport km per capita per day Non-car km per capita per day Car-km per capita per day Car fuel consumption per capita per day (litres) Percent electric cars

Matrix Indicators

The *Transport Submodel* produces a result file with matrix information for the beginning und end of each simulation period.

The matrix result file contains 104 square matrices of dimension n x n (where n is the number of zones) for each simulation period year, i.e. for 20 periods 104x20+92 = 1,172 matrices. Of the 104 matrices there are:

4 matrices of equilibrium travel times (4 modes),
4 matrices of equilibrium travel distances (4 modes),
4 matrices of equilibrium travel costs (4 modes),
16 matrices of equilibrium trip utilities (4 income groups, 4 modes),
64 matrices of equilibrium trips (4 trip purposes, 4 income groups, 4 modes)
4 matrices of job changes (4 income groups)
4 matrices of migrants (4 income groups)
4 matrices of migrant households (4 income groups)

Link Indicators

The *Transport Submodel* produces a result file with link information for the beginning und end of each simulation period. The link result file contains for each simulated year

- number of vehicles by vehicle type,
- number of travellers,
- percent capacity utilisation

of each link of the combined public transport and road network at user-optimum network equilibrium.

Raster Indicators

The IRPUD model is linked to the *Raster Model* calculating spatially disaggregate traffic noise and air pollution indicators.

More information about the Raster Model can be found at http://www.spiekermann-wegener.de/mod/rastermod.htm).

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