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D4.1.3

Conceptual and quantitative system dynamics integrated framework to analyse rural-urban land use relationships including growth and shrinkage in the case study region Leipzig-Halle

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SIXTH FRAMEWORK PROGRAMME

Contents

Abstract

The objective of D4.1.3 is to present a conceptual and quantitative system dynamics integrated model to analyse rural-urban land use relationships including growth and shrinkage in the case study region of Leipzig-Halle. The methodology used is system dynamics modelling (SD). The results of the work can be summarised as given below:

Popular science description of main results:

D4.1.3 presents a simulation model that is able to compute both growth and shrinkage processes in urban regions. Using a system dynamics approach, we uncover nonlinear dynamics and feedbacks between demography, housing preference and supply of housing space. The simulation results show that despite population decline, the increasing number of single households leads to a growing total housing demand in the central parts of the study area. Beyond this area, residential vacancies in multi-storey housing segments will remain regardless of population growth. At the same time, the simulations show that despite population shrinkage and an overall oversupply of flats, there is a negative net-demand of flats in affordable prefabricated housing estates as the percentage of low-income households increases. These findings will help planners modify or adapt their visions of the residential function in shrinking cities and to adjust current programmes of renewal and restructuring.

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Spatial scale for results: Regional, national, European	Regional
DPSIR framework: Driver, Pressure, State, Impact, Response	Driver, Pressure, State, Impact, Response
Land use issues covered: Housing, Traffic, Agriculture, Natural area, Water, Tourism/recreation	Housing, green space
Scenario sensitivity: Are the products/outputs sensitive to Module 1 scenarios?	Yes, the outputs are based on the population projections of M1.
Output indicators: Socio-economic & environmental external constraints; Land Use structure; RUR Metabolism; ECO-system integrity; Ecosystem Services; Socio-economic assessment Criteria; Decisions	Socio-economic external constraints; Land use structure; Socio-economic assessment Criteria
Knowledge type: Narrative storylines; Response functions; GIS-based maps; Tables or charts; Handbooks	Response functions

How many fact sheets will be derived from this deliverable:	**1**

Introduction

D4.1.3 will be printed in Environment and Planning B in due course. Here we added the revised version of the paper.

Simulating demography and housing demand in an urban region under scenarios of growth and shrinkage

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Abstract

After the fall of the Berlin wall in 1989, demographic decline and urban shrinkage has brought massive changes in housing stock in East German cities. Urban planners and policy makers face complex problems caused by the resulting vacancies and demolitions and the handling of urban brownfields in the inner city. At the same time, cities are under the ongoing pressure of suburbanisation. Because existing models mainly focus on demographic and urban growth and their impact on housing stocks, we present a simulation model that is able to compute both growth and shrinkage processes. We uncover nonlinear dynamics and feedbacks between demography, housing preference and supply of housing space. The simulation results show that despite population decline, the increasing number of single households leads to a growing total housing demand in the central parts of the study area. Beyond this area, residential vacancies in multi-storey housing segments will remain regardless of population growth. At the same time, the simulations show that despite population shrinkage and an overall oversupply of flats, there is a negative net-demand of flats in affordable prefabricated housing estates as the percentage of low-income households increases. These findings will help planners modify or adapt their visions of the residential function in shrinking cities and to adjust current programmes of renewal and restructuring.

Keywords

Urban simulation, residential space, demographic change, households, Germany

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1. Introduction

The simultaneity of demographic change, suburban growth and inner-city shrinkage is a challenge for urban planners and policy-makers in post-industrial, modern societies in both Europe and the US (Batty, 2001; Champion, 2001; Kasanko et al., 2006). This situation is particularly true for cities that were situated behind the iron curtain and entered a phase of extreme population dynamics after 1990 – that is, rapid and massive inner-city out-migration along with suburban net-growth (Kabisch, 2005). A vivid example of these developments is the city of Leipzig, Germany. The city is representative of a wider range of large, post-socialist cities in Eastern Germany, but also Central Eastern Europe (Banzhaf et al., 2007; Haase et al., 2007). Apart from population losses due to labour-migration into the western part of Germany, the main reason for the simultaneity of sprawl and shrinkage is a quantitative and qualitative change of the urban demography and respective housing-demand-patterns. In addition to typical suburbanites, such as family households, we increasingly find "non-traditional" household types, such as cohabitating flat-sharers and single-parent families or patchwork families with specific housing preferences (a.o. Bösch-Supan et al., 2001; Buzar et al., 2007). The absolute and relative growth of the latter was found to foster the current reurbanisation processes in inner-city residential areas (Buzar et al., 2007; Haase, 2008), whereas the former drives the ongoing sprawl (Couch et al., 2005).

However, such changing housing demand patterns due to demographic changes are far from just a phenomenon in former socialist countries; throughout Europe, the population is getting older and the share of traditional family households is decreasing (Kaa, 1987, 2004). Meanwhile, population decline in urban regions is a trend across Europe (Kabisch & Haase, in press). However, these effects are not well represented in urban simulation models because the models focus predominantly on urban sprawl and growth (Schwarz et al., in press).

Simulation models can help us understand these complex dynamics and derive scenarios for the future (Verburg et al., 2004). In this study, we develop a simulation model for urban regions with a focus on two identified missing links: demographic changes in household types and simultaneous growth and shrinkage. In doing so, we aim at uncovering feedbacks between both declining and growing housing development. In both cases we account for ageing population, respective housing preferences and their impact on the housing stock.

Because urban planning and housing companies both look for projections of future housing demand based on new demographic and household behaviours (Jessen, 2006), new knowledge of the above-mentioned feedbacks is crucial. Therefore, our study pursues the following objectives:

1. Building a model that covers dynamics and feedbacks between population development, households, residential demand and housing supply within an urban region.
2. Revealing feedbacks between population (growth and shrinkage), household preferences, residential demand and housing supply, including vacancies.
3. Answering the following questions posed by urban planning:
   - Does a shrinking city face ongoing residential land consumption?
   - Does a growth of one-person households increase the housing demand?

The paper is organised as follows. After introducing the problem of modelling urban housing demand under conditions of demographic change, section 2 provides details of the modelling approach, the software chosen and the case study of Leipzig. The model components and equations are discussed in section 3 before coming to the major results (section 4) and their discussion in section 5. The paper closes with an outlook concerning future amplifications of the model.

2. Modelling demographic effects on housing demand

2.1 State-of-the-art in urban causality modelling

A variety of simulation models for urban land use changes have been developed to assist in urban planning (see reviews by EPA, 2000; Berling-Wolff and Wu, 2004; Haase and Schwarz, 2009). Four different urban modelling approaches can be distinguished: (1) system dynamics; (2) spatial economics / econometric models; (3) cellular automata; and (4) agent-based models. (1) System dynamics models are – in their standard application – not spatially explicit. Rather, the structure of combining stocks, flows and feedback mechanisms leads to a set of differential equations (Sterman, 2000). The outcome of these equations can be simulated, given values for parameters and initial conditions (for urban system dynamics, see, e.g., Forrester, 1969; Haghani et al., 2003a, b; Raux, 2003). (2) Spatial economics / econometric models (e.g., Nijkamp et al., 1993; Mankiw and Weil, 1989) mainly examine demography and household-driven demand-supply relations in urban regions, such as housing market developments. (3) Land use change models use cellular automata with 2-dimensional grids. Each cell symbolises a patch of land, and change rules depend on empirical data regarding land use changes in the past and on suitability and zoning regulations (e.g., Verburg and Overmars, 2007; Landis and Zhang, 1998a, b; Engelen et al., 2007). Cells change states simultaneously according to the same rules, and the state of a cell in time t solely depends on the state of the neighbouring cells in t−1. (4) Agent-based models consist of autonomous individuals (agents) that are usually located on a spatially explicit grid. The agents perceive their environment and interact with one another (Parker et al., 2003). In urban land use models, they represent, for example, households relocating their homes (e.g., Strauch et al., 2003; Salvini and Miller, 2005; Ettema et al., 2007; Loibl et al., 2007; Waddell et al., 2003).

Shrinkage poses challenges for these simulation models because the models are mostly developed for growing cities in industrialised countries. To expand such simulation models to cover urban shrinkage, two additional factors need to be included: (1) residential vacancy as an output variable; and (2) the processes of deconstruction and demolition of vacant residential areas. Few existing simulation models explicitly include the vacancy and demolition of residential housing stock (e.g., Forrester, 1969; Sanders & Sanders, 2004; Eskinasi and Rouwette, 2004).

2.2 A new system model approach

Building on the findings of section 2.1, we decided to construct a new urban simulation model that is able to capture both population growth and shrinkage. Although our new model is calibrated using regional statistics and survey data from the urban region of Leipzig, the model approach itself is applicable to other urban regions with a comparable mix of traditional and non-traditional household types (Haase & Haase, 2007).

System dynamics represent an appropriate tool for identifying causal-feedback-loops occurring in an urban region and building a respective model. We have chosen the system dynamics approach for the following reasons:

(1) In a system dynamics model, specific variables interact in the form of causal feedback loops, which, depending on their polarity, change the system state in a (largely) non-linear way (Forrester, 1971, 1979; Dhawan, 2006; Sterman, 2002). For both growth and shrinkage, including feedback loops in a model is important: on the one hand, growing industrial or residential areas might grow even faster because

they attract more growth; on the other hand, a declining residential area may become more unattractive for residents already living there, thus causing even faster decline.

(2) System dynamics models are, in general, not spatially explicit, although sectors or other spatial units can be introduced into such models (Sanders and Sanders, 2004). When setting up a new model approach, working with aggregate, non-spatial data to capture the main causal relations is, in fact, a good starting point. For modelling shrinkage, these data provide another clear advantage, as empirical data on the spatial distribution of vacant residential or commercial areas are difficult to find.

(3) System dynamics models are suitable, and are often used, for deriving scenarios and future projections (see examples in Eppink et al., 2004; Forrester, 1969; Onsted, 2002; Raux, 2003; Sanders and Sanders, 2004). Simulating simultaneous urban growth and shrinkage is extremely helpful for scientists as well as practitioners when estimating future land use changes as well as the demand for residential land. In our model, population development (input variable) affects the demand on housing areas, which (indirectly) depends on factors such as housing costs and urban green spaces (system parameter). These factors, in turn, lead to a modification of variables such as housing area and housing vacancy (output variables). Expressed mathematically, system dynamics models consist of differential equations that are estimated for each time step (in our model, once per year). The model presented was implemented using the modelling environment Simile (version 4.7) by Simulistics (Simulistics Ltd., 2007). Simile provides a graphical user interface and is based on C++ (Muetzefeldt and Massheder, 2002; Muetzelfeldt, 2002). The specifications of our model in terms of variables and equations are given in section 3.

2.3 The case study

The region of Leipzig, Germany, was chosen as an example of the quantification of causal loops. Leipzig is a stagnating-to-shrinking rural-urban region of half-a-million inhabitants located in Eastern Germany. The compact, monocentric urban region holds one of the largest Wilhelminian (1890-1918) housing estates in all of Germany and one of the largest socialist prefabricated high-rise housing complexes (Haase & Nuissl, 2007).

In the nineteenth century, Leipzig experienced a period of vibrant industrial growth, making it the country's fourth largest city when it reached its population peak of more than 700,000 in the early 1930s (Couch et al., 2005). During the socialist period, between World War II and 1990, the city's population declined.

Since the German reunification, the development of Leipzig has mainly been influenced by de-industrialisation, further population losses and residential vacancies. During the 15 years after the reunification, the city lost about 100,000 inhabitants (1989: 530,000; 1998: 437,000). In 2006, Leipzig had 505,000 inhabitants. Simultaneously with the population decline, urban sprawl emerged at the city's periphery. Scattered commercial and residential development occurred in the surrounding rural landscape (Nuissl and Rink, 2005).

Leipzig has a quasi-radial structure. The Wilhelminian-era multi-storey housing estates form the inner residential ring around the town's centre. A second ring consists of mixed residential-industrial areas characterised by multi-storey row houses and villas. As a third ring, single houses and residential parks follow along the urban-to-rural gradient adjacent to the villages of the suburban and rural surroundings.

3. The model

3.1 Structure

The system considered in our model represents a city and its close surroundings. Here we find typical urban structure types (UST) as described in section 3.2. Structurally, the model distinguishes demand and supply.

The model uses population and household dynamics to compute a household-preference-driven housing demand. The respective supply, represented by the housing stock of each UST, in turn influences this demand. Based on the demand-supply ratio, residential vacancy and demolition of houses is determined in addition to new construction of houses. Thus, components for shrinkage and growth are included. In the following, the model components are introduced in more detail (Figure 1).

Figure 1

Population is dynamically estimated by fertility, mortality and migration and is classified by age classes, which are then classified into different household types (HHT; eqs. 1 and 2). Households have specific preferences regarding the desired housing area, such as surrounding urban green spaces, housing costs, house type, social characteristics of the neighbourhood and crime rates (Figure 1).

In total, seven HHTs (see below for more details) decide on their living spaces based on their specific preferences. If there is not enough demand for a certain UST, the living space is abandoned and it becomes a residential vacancy. A vacant housing space, if not demanded, is demolished and the area converted to open land. If the demand for a certain structural type increases, the open land is then converted into a new housing area by construction. Figure 1 shows that a change in the supply side, reflected in the real estate, affects the housing conditions of a UST, which again influences the housing demand. Thus, the feedback from supply to demand is considered.

3.2 Model components

Population

One of the main components of the simulation model is the total population number P, which depends on the temporal dependence dP/dt of total fertility F, mortality μ due to life expectancy and net-migration. Individuals may enter a population cohort i of a region, either by birth $F*P$ or in-migration I. The exchange of persons between cohorts is unidirectional from younger to older cohorts; this is reflected in the ageing process, which is represented by the aging rate A. Leaving a cohort occurs by ageing, out-migration O or dying μ_i*P, coded as the cohort output (eq.1):

$$\frac{dP_i}{dt} = \sum_{i=2}^{3} F_i \cdot P_i - \mu_i \cdot P_i + I_i - O_i + A_{i-1} \cdot P_{i-1} - A_i \cdot P_i \qquad (1)$$

with $F_{1,5-8} = 0$, $\mu > 0$, $I, O > 0$.

Households

Empirical research has shown that household characteristics significantly influence the specific housing demand per person (Buzar et al., 2007). Therefore, the aggregation of individual elderly person classes into households is relevant, especially in terms of residential preferences. Households vary considerably in form and size, and this variety increases even within the context of demographic change (Kaa, 2004). As households become smaller and less stable, they become more subject-oriented, and living arrangements are adapted to individual narratives (Buzar et al., 2005; Ogden and Hall, 2000).

Households have been classified according to type based on recent empirical data for different European cities: families with dependent children; elderly one-person households and couples (co-habitation); and so called ‘new’ or ‘non-traditional’ household types, namely, young one-person households, young couples or cohabitation households, single-parents and unrelated adults sharing a common flat (Buzar et al., 2007). In the model, the household types $\overrightarrow{HHT}$ at a point in time t are coded as the following distribution matrix $M(t)$ of these seven HHTs (eq. 2):

$$\overrightarrow{HHT}_{1\ldots7} = (M_{1\ldots7}(t) + N(t))\vec{P} \qquad (2)$$

$M(t)$, the distribution matrix, has a linear trend $N(t)$ according to the changes that are assumed to come along with demographic changes due to the second demographic transition, such as an increase of single households and a decrease of the classical family household (cf. Kaa, 2004).

A specific mean income MI_k is also assigned to each household (Haase, A. et al., 2005) (a.o. determines the preference for large houses, flats and green space). Due to limited empirical data, an income variation is randomly created, whereas a threshold determines to which preference set an HHT is given priority (Figure A1). A household with high income is less restricted by the price of a flat and looks more at housing conditions such as green space availability or security.

Urban Structure Types (USTs)

We coded eight urban structure types that are representative of European urban regions, including the core city and the periurban area (Ravetz, 2000). For the core city, these USTs are town centre (1); Wilhelminian-era, old built-up blocks (inner city housing estates) (2); multi-storey row housing estates (built-up in the 1960-70s) (3); prefabricated multi-storey housing estates (from socialist times) (4); villas (5); residential parks (mainly small, uniform single houses) (6); and single houses (7). The periurban area is represented by suburban villages (8).

Housing preferences

The concept of residential segregation suggests that household patterns do not occur by accident, but can be related to the attractiveness of a place j depending on housing preference variables (Gober, 1990; Wegener and Spiekermann, 1996; Kemper, 2001). Next to income as a household type specific variable, the real estate market in the form of space availability/supply SS, the building state BS, and the costs of buying or renting a flat or a house C, play an important role. Moreover, the direct social and environmental neighbourhood are decisive for a residential choice (Haase et al., 2008).

In the model, crime rate Cr, green supply G, surroundings Su, social neighbourhood So, centrality Ct and education facilities E represent the neighbourhood. Rules for housing demand and its magnitude based on preference variables were derived from different questionnaire surveys conducted in Leipzig to identify housing satisfaction (Haase, 2008; Haase et al., 2005; Kabisch, 2005). The availability of such housing satisfaction data is crucial for model transfer to other urban regions (cf. section 2.1).

Based on a ranking of the relative importance of neighbourhood characteristics for residents, we chose a simple additive weighting for coding the attractiveness of a place for each household. The variable's importance of each HHT is included according to their estimated importance and weighting. Additive weighting assumes the additive aggregation of the criterion values, which are normalised into non-dimensional values ranging between 0 and 1 to make them comparable by means of the value functions. The residential attractiveness of a place RA_{kj} to live is coded as given in eq. 3:

$$
\begin{aligned}
RA_{kj} = {} & CtP_k \cdot CtC_j + SutP_k \cdot SutC_j + CP_k \cdot CC_j + BSP_k \cdot BSC_j + CrP_k \cdot CrC_j \\
& + EP_k \cdot EC_j + GP_k \cdot GC_j + SoP_k \cdot \sum_{j=1}^{7} (SoC_j \cdot SoPM_k)
\end{aligned}
\qquad (3)
$$

Multiplication of the household's specific preferences (k) and the given site conditions of the neighbourhood (j) produces a maximum preference and an initial probability of the household distribution within the eight USTs. Preference variables such as *CtP* or *SutP* are static parameters, while condition variables such as *CtC* or *SutC* depend on the demand–supply relation (Appendix A1). Rising living costs of a UST may have a negative effect on its attractiveness and, by implication, on the UST demand.

Depending on the number of persons per household, we calculate the number of housing demand agents DP_{kj} (eq.4) and the respective housing area demand in hectares (eq. 5):

$$DP_{kj} = RA_{kj} \cdot HHT_k \qquad \text{with } \frac{dDP_{kj}}{dHHT_k} \geq 0,\ t > 0 \qquad (4)$$

$$DLS_{kj} = \frac{LSC_k \cdot DP_{kj}}{10000} \qquad \text{with } \frac{dDLS_{kj}}{dDP_{kj}} \geq 0,\ t > 0 \qquad (5)$$

LSC_k is the housing area per capita in m^2. DLS_{kj} represents the demanded living space for each HHT k and UST j. The supplied living space SLS_j is calculated using the newly built-up area co_j, flat abandonment and depletion of housing stock df_j, demolition dl_j and re-filled vacancies ru_j, which are considered because of reurbanisation trends (Buzar et al., 2007):

$$\frac{SLS_{kj}}{dt} = \sqrt{co_k \cdot DLS_{kj} - df_k \cdot DLS_{kj} - dl_k \cdot DLS_{kj} + ru_j \cdot DLS_{kj}} \qquad \text{with } t > 0 \qquad (6)$$

The residential vacancy V_j is determined by the annual demolition rate dl_j. The parameters co_j, df_j, dl_j, and ru_j are all highly influenced by the demand for living space DLS_{kj}. The demand adaption as a consequence of changing supply is regulated by the changing condition variables of each UST, such as housing costs or crime rate (Figure A1). Here, further testing and more empirical data are necessary for a precise validation. Any causal loop from housing supply to household structure has not yet been considered.

Finally, the net-demand on housing area is (eq. 7):

$$NDLS_k = DLS_k - SLS_k \qquad (7)$$

Vacancies and demolition

In the case of non-satisfaction of a household's residential demands, out-migration increases. The share of residential vacancy increases simultaneously in the parts of the city that do not fulfil, or only partially fulfil, the housing requirements of the households (Kabisch, 2005). Vacancy occurs either in the form of single dwellings within a house or completely vacant housing estates (100% vacancy). We further assume that, according to the life-cycle or 'ageing' process of a residential house, a house proves to be uninhabitable after being vacant for over five years, and both maintenance and reconstruction costs far exceed the rental income from new residents (in low income areas of Leipzig). Houses that have a more attractive urban structure type can be re-filled (cf. eq.14). The resulting demolition dl_i rate is coded accordingly in the model (see appendix). The open land, which partially reflects the space supply for new construction, changes as a consequence of the total newly-built areas and the total demolished living space at time t. A complete description of the model variables, including all initial values, can be found in the appendix.

3.3 Calibration and validation of the model

Before running different population scenarios, the model's functionality was tested to verify its quality. A time series produced by the model (with real data inputs) was compared to data from the case study. Table 1 provides an overview of all model variables used for model calibration. The data were taken from municipal statistics for 2005 (City of Leipzig, Saxony; Table 1).

Table 1

Using independent census data, that is time series of municipal statistics from 1992-2005 (City of Leipzig, 1993-2006), the major variables of the simulation model could be validated. Figure 2 reports the regression coefficients and curves obtained. For all variables tested, they show that the model results are in good and significant accordance with the statistical data (R-square >0.7). To confirm that the validation of the model was correct and did not relate to the calibration data, two independent data sets were used (the calibration using federal census data, the validation using municipal census data).

Figure 2

3.4 Scenarios

In the introduction, we posed several questions concerning how housing demand and supply and residential vacancy would be affected if the population in an urban area either grows or declines. In accordance with these questions, a scenario matrix was set up for population growth, population shrinkage and baseline development (representing a continuation of current population development trends). These factors were based on the major demographic variables the model uses, such as fertility, mortality, net-migration and percentage of single and family households. These variables predominantly shape the current population dynamics of an urban region (Table 3). The simulations cover a time horizon of 25 years (2005-2030 for each of the scenarios).

Table 2

4. Results and discussion

4.1 Population development

The results of the scenarios show a differentiated picture for population development. Starting with today's urban population (514,904), the baseline scenario shows a non-linear but gradual population growth (564,585) until 2030 (Figure 3). In the shrinkage scenario, however, the population number falls remarkably (again non-linear) to under 400,000. Assuming a constant increase of fertility and net-migration, the population rises above 640,000 residents in 2030. Within just 25 years, the difference between the growth and shrinkage scenarios accounts for more than one-fourth of the current total population number.

Figure 3

When looking at the development of the age class, the baseline, growth and shrinkage scenarios differ considerably. Using the indicator of the young- (share of inhabitants <20 years old divided by the share of inhabitants >60 years) and old-age dependency rates (1/young-age dependency), we see that the young-age dependency in each of the three scenarios decreases – which means that the urban region will age. A considerable increase in the old-age dependency rate can be found in the shrinkage scenario: more than 2.5 persons >60 years equals one person <20 years. Figure A3 (Appendix) reports that in the shrinkage scenario, the decrease in population accelerates after 2015. Due to an aging population, the housing preferences and demands of elderly people will attract special attention to future housing markets (Kaa, 2004; Buzar et al., 2007).

4.2 Household development

The growth of the total number of households in both the baseline and growth scenarios is caused by an increase in the number of persons living in single households (young and elderly) (Figure 4). This result is in accordance with current observations of household number (Buzar et al., 2007), which is assumed to be caused mainly by on-going individualisation trends (Ogden and Hall, 2000). The growth scenario, in particular, reports a non-linear growth of young single households, which no doubt has implications on the need for housing area. After an initial increase, the number of single households decreases in the shrinkage scenario. Compared to the increase of persons living in single households, the number of family household members dramatically decreases in all three scenarios. Conversely, the number of single-parent families increases in both the baseline and growth scenarios (Figure 4).

Figure 4

4.3 Housing demand and supply

Figure 5 depicts the net-demand-supply from 2005-2030. We see a completely different picture for the growth and shrinkage scenarios: whereas the housing supply exceeds the respective demand in times of population shrinkage, in times of population growth, the housing supply dramatically decreases (assuming that individual living space will not be reduced) (Priemus, 2003).

Figure 5

In the growth scenario, an undersupply of prefabricated multi-storey houses is simulated, something that would not be expected based on the low perception of this urban structure type today (Kabisch et al., 1997). In the simulation, there is a growing interest in affordable flats by low-income and single-parent family households that can be provided by prefabricated large housing estates. As Figure 5 shows, the undersupply levels-out by about 30%. In all other urban structure types, an oversupply is computed even for the growth scenario, although there is a high preference by most of the households for single houses, Wilhelminian-era built-up houses or residential parks and villas. The sharp decrease in housing demand is caused by the reduction of the population by >100,000 residents by 2030 in the shrinkage scenario, which can neither be moderated by an increase in the number of households nor by the demolition of vacant houses.

4.4 Vacancies and demolition of residential supply

As discussed in the introductory section, residential vacancy is a major issue in urban land use development, particularly under conditions of shrinkage, is a consequence of an oversupply of living space (apartments, houses). Figure 6 gives an idea of the proportions of residential vacancy in the different urban structure types.

Figure 6

The overall share of vacancy increases in the shrinkage scenario up to 13% by 2030, whereas it falls to 6% in the growth scenario (starting with 12.3% in 2005). Even in the baseline scenario, residential vacancy will decrease to 9.1%. In the growth scenario, demolition predominantly impacts the proportion of residential vacancies in the prefabricated multi-storey housing estates, as they are less attractive than other USTs for single and family households with a higher income (and for most of the urban planners). This result somehow contradicts the discussed undersupply of prefabricated housing shown in Figure 5, and it makes clear that current demolition policies underestimate the demand for affordable flats in such prefab housing estates caused by a future increase of low-income household types.

The reduction of vacancy in the inner-urban Wilhelminian-era blocks mainly results from their rising attractiveness for a growing number of households. Demolition does not occur in single housing areas. Therefore, we find a slight increase in single house vacancy in the shrinkage scenario. There is no empirical evidence from European urban regions that single houses are demolished on a larger scale even if vacancy appears (Kasanko et al., 2006).

The total residential area of the urban region, summing up demand and supply on living space as well as residential vacancy moderated by demolition measures, shows again a highly divergent picture. The graphs in Figure 7 show that Leipzig will face an increase in the total residential area in the case of population growth, which means that the urban region will expand and, assuming a constant or even increasing living space per capita, further land consumption will take place. In the baseline scenario, remaining residential vacancies and low population growth lead to smart urban growth.

In the urban shrinkage scenario, residential land will decrease (in the model, this leads to an increase in open land) in cases when all residential areas that are unused are given back to nature (Figure 7). Open land consumption does not happen in the baseline scenario. Here, the surplus in residential land compared to the start of the simulation in 2005 is buffered with a densification of the existing urban space and an infill of vacancies. We observe a dramatic decrease of open land in the growth scenario.

Figure 7

Figure 7 further shows that an alteration in the distribution of households – that is, according to the second demographic transition, an increase of single households and the reverse development for family households – has an impact on the growth/decline of the total residential area.

5. Conclusions

Based on the results of the new simulation model, we can show a range of interesting trajectories concerning how population dynamics under demographic change will affect housing demand and the supply of residential and open land in an urban region. The results of the population projections show that currently shrinking cities and urban regions can expect very different futures; further decline is only one of them. In accordance with recent findings on reurbanisation, trends in urban regions formerly faced with population decline (Turok and Mykhnenko, 2006; Storper and

Manville, 2006), in both baseline and growth scenarios, indicate that urban regions might again “recover” from a phase of decline.

The model shows strong and weak segments of the housing stock related to two important urban processes: demographic change and new household types as well as urban growth and shrinkage. The results shown here can help planners better understand housing preferences and the feedbacks between those and the housing supply (= housing stock).

Do shrinking cities face further residential land consumption? Does a growing number of single-person households lead to an increase in the overall housing demand? In two of these scenarios (baseline and the growth), we state an increase of single households, both younger and elderly. This increase leads to an increase in the total housing demand in both scenarios (cf. Figures 3 and A4). Compared to this, In the shrinkage scenario, neither the number of single households nor the housing demand increases. In Leipzig, we note an increase in the total number of households up to 2007. However, the expected increase in housing area weakens and is expected to abate within the coming years.

As shown in the summarising Figure 7, a growing number of single households leads to an increasing demand of living space and residential land taken in both total population growth and shrinkage scenarios due to the positive trend of per capita living space. A total decline in population does not “solve” the land consumption problem of urban regions as long as per capita demands are rising and individualisation leads to an increase in total household numbers (Karsten, 2003; Lee et al., 2003).

Figure 7

The results of our model show that young single households could play an important role in new, inner-city development in the Wilhelminian-era ring – that is, the process of reurbanisation – as inner-city urban structure types, in particular, are positively influenced by an influx of young single households. This effect may be crucial to overcoming residential vacancies in inner-city areas. Young singles, especially, demand a “functional social and cultural life”, which is offered in the inner city (Favell, 2008). In addition, it was shown that the development of family households implies the direction of single-house progress linked to future land consumption. In contrast, if the decrease in family households continues, previous sprawling processes at the city’s periphery can be expected to freeze.

Of particular interest for urban planners are the housing demand and respective land use development trends. The former high vacancy rates of Leipzig’s inner-city will balance the growing demand of a living space of 36 hectares, and continuing demolition will even lead to a reduction of the residential area by 10 hectares by 2020 (baseline; Table A 2). Therefore, a high potential for open spaces and greenfield expansion exists, which could enhance the attractiveness of the inner-city. The rising demand for inner-city Wilhelminian-era USTs, which define the urban image, requires a reduction of the demolition rate (despite existing vacancies). With decreasing growth sprawl affecting residential areas, detached houses will still increase by 38 hectares by 2020, while enormous 108-hectare areas will become available due to demolition in the segment of prefabricated multi-storey houses (shrinkage; Table A1). This trend elucidates the high brownfield exploitation capability for new construction, which can prevent further space consumption and sealing.

Another possible way of using our model is combining it with a spatial cellular automaton to uncover local dynamics. The presented model delivers population dynamics and housing demand, including internal causal feedback loops on the regional scale, to avoid simple empirical trend implications.

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Tables

Table 1. Variables used to calibrate the model (all initial values can be found in the appendix).

Population	Household types	Housing market
Population (P_i)	Distribution matrix (DM_{xk})	City area (CA)
Fertility (F_i) + trend* (FT_i)	Housing preferences (CtP_j, SuP_j, CP_j, BP_j, CrP_j, EP_j, GP_j, SoP_j)	Site conditions (CtP_k, SuP_k, CP_k, BP_k, CrP_k, EP_k, GP_k, SoP_k)
Mortality (M_i) + trend* (MT_i)	Mean income (MI_j)	Housing area (SLS_k)
In-migration (IM_i) + trend* (TOM_i)		Vacancy (V_k)
Out-migration (OM_i) + trend* (TOM_i)		Open land (SS)
		Number of floors (St_k)
		Housing floor density (FSM_k)

* derived from statistical data from 1999-2005

Table 2. Calculation of fertility, mortality, net-migration, percentage single households and families based on municipal and regional statistics. FT = measured fertility rate 1999-2005; MT = measured mortality rate 1999-2005; IMT and OMT = measured migration rates 1999-2005.

Scenario	Fertility (F)	Mortality (M)	In-Migration (IM) Out-Migration (OM)	% Single households (S)	% Families (Fa)
Shrinkage	*F= (F0*FT)*(-0.2)*	*M= (M0*MT)*(-0.2)*	*IM= IM0+IMT*(-1),* *OM= OM0+OMT*(-0.95)*	*S= S(t-1)*(1+0.002*t)*	*Fa= Fa(t-1)* (1+0.002*t)*
Baseline	*F= (F0*FT)*(0.8)*	*M= (M0*MT)*(0.8)*	*IM= IM0+IMT*(1),* *OM= OM0+OMT*(0.96)*	*S= S(t-1) +S*0.008*t*	*Fa= Fa(t-1)+Fa*0.008*t*
Growth	*F= (F0*FT)*(2)*	*M= (M0*MT)*(1.5)*	*IM= IM0+IMT*(1.01),* *OM= OM0+OMT*(1.01)*	*S= S(t-1) +S*0.002*t*	*Fa= Fa(t-1)+Fa*0.002*t*

Figures

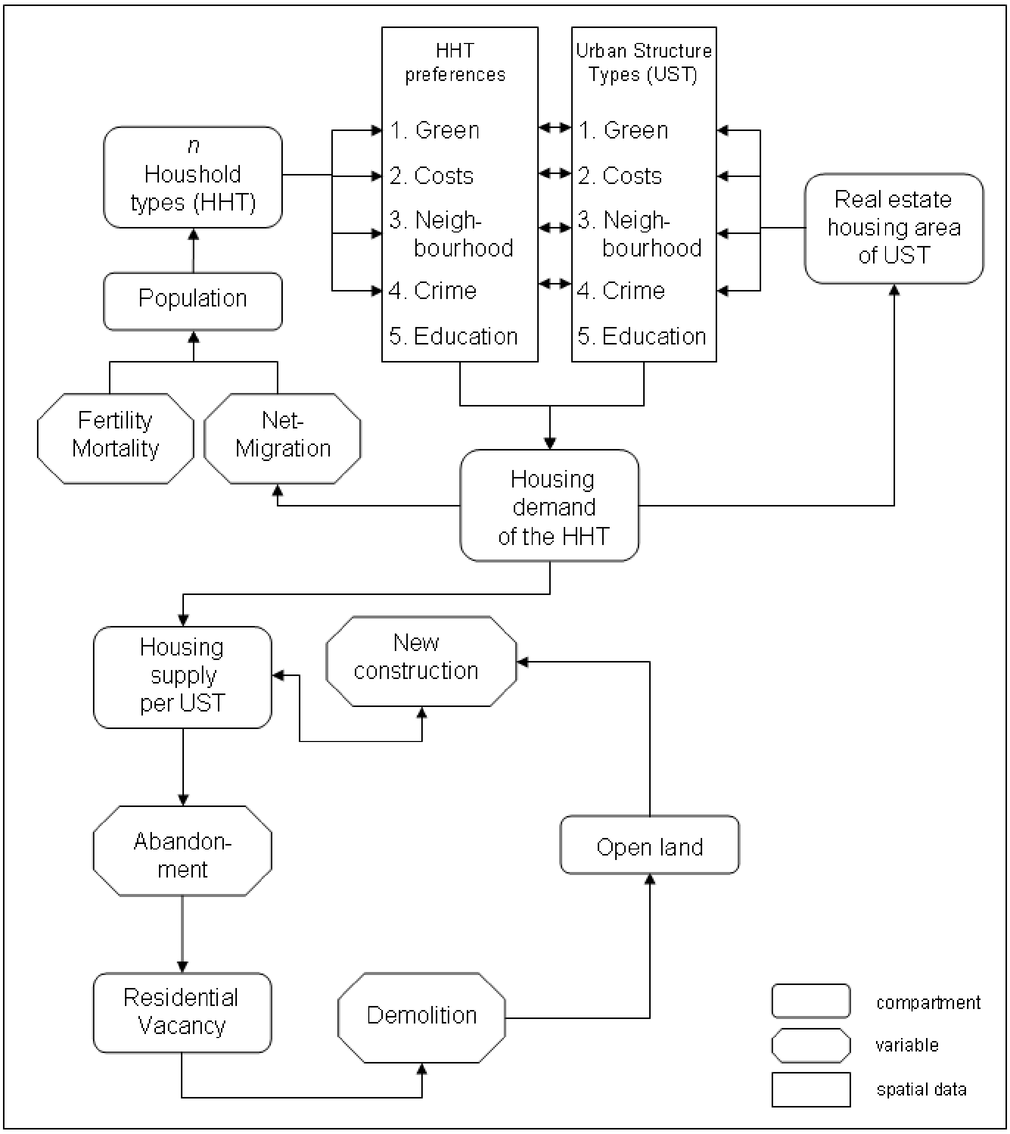
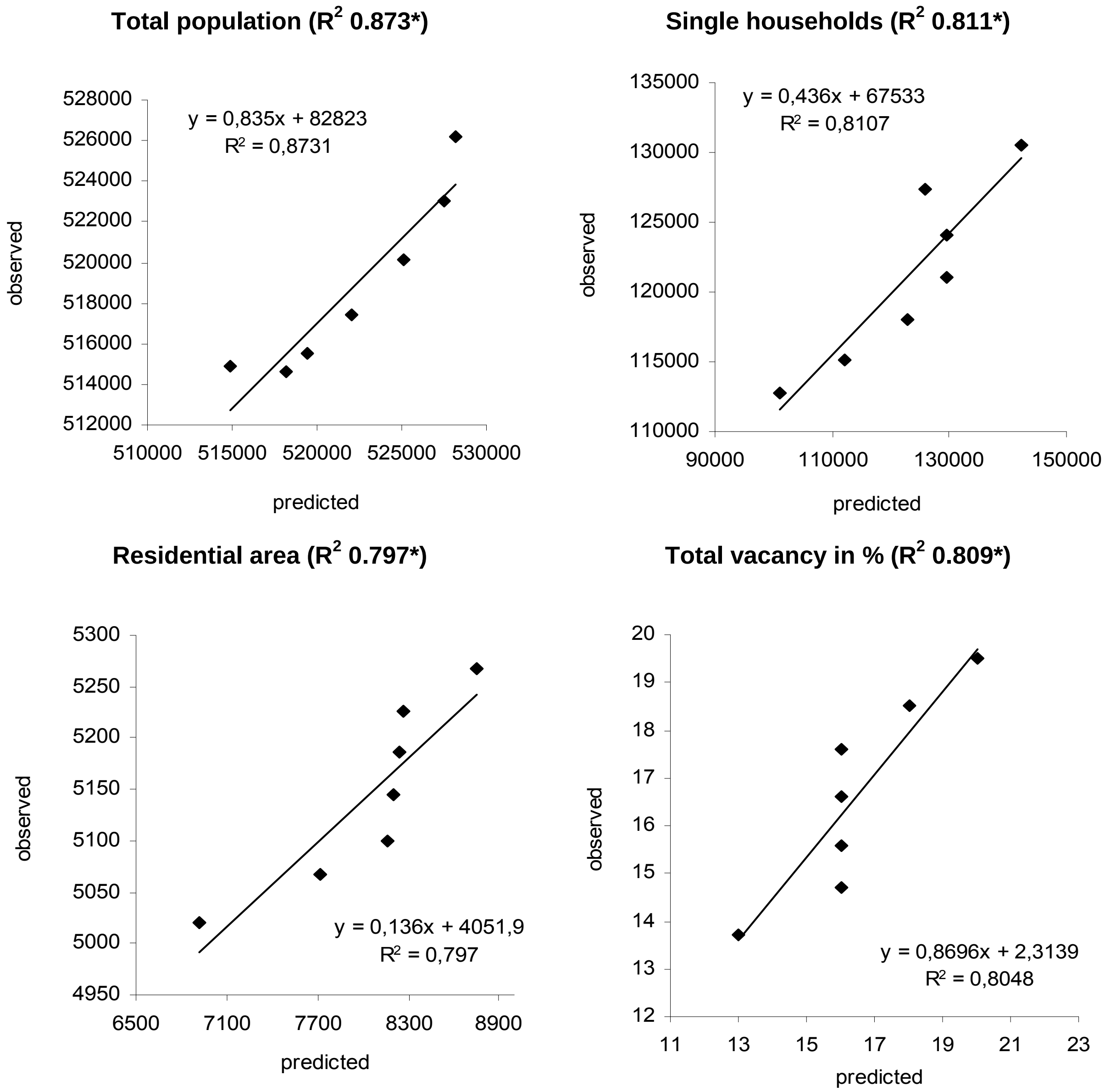


Figure 1. Simplified model structure including the main model components.



** $p < 0.01$ * $p < 0.05$ (t-test)

Figure 2. Regression coefficients obtained during the model validation using municipal statistics (issued by the city of Leipzig, 1993-2006).

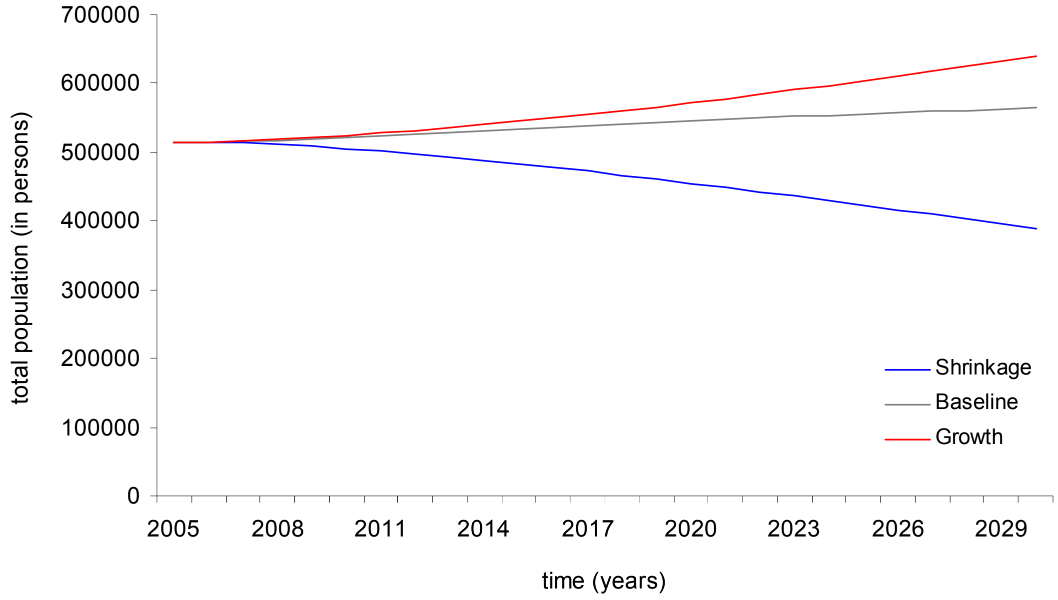


Figure 3. Total population in persons for baseline, growth and shrinkage scenarios.

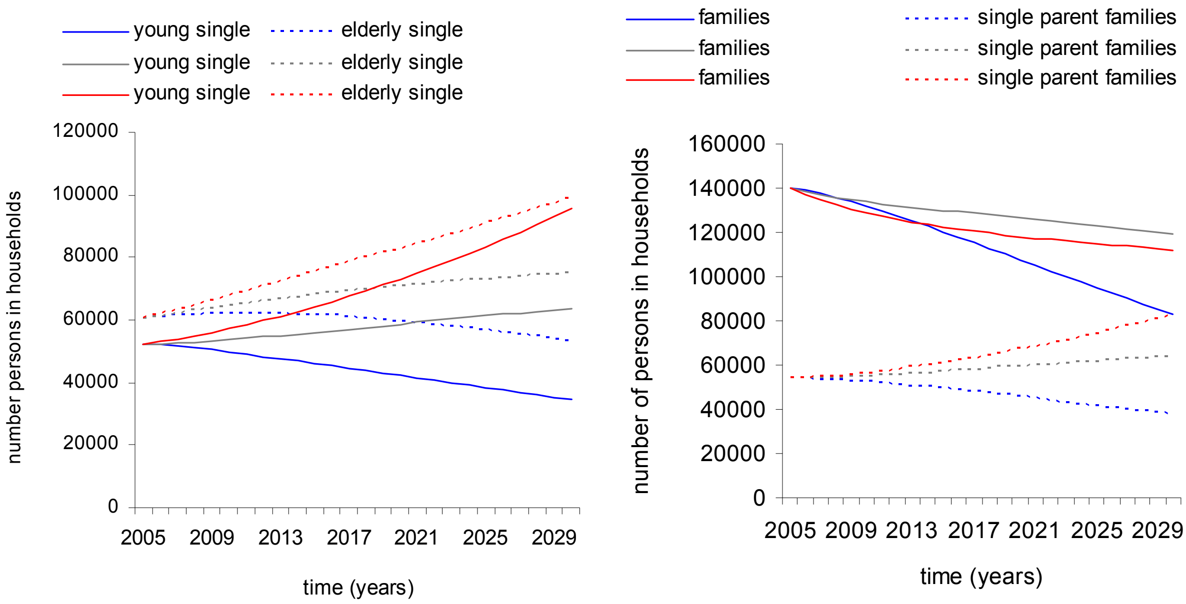
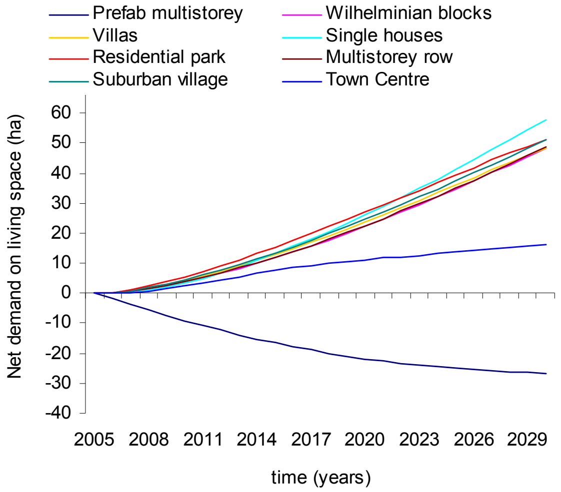
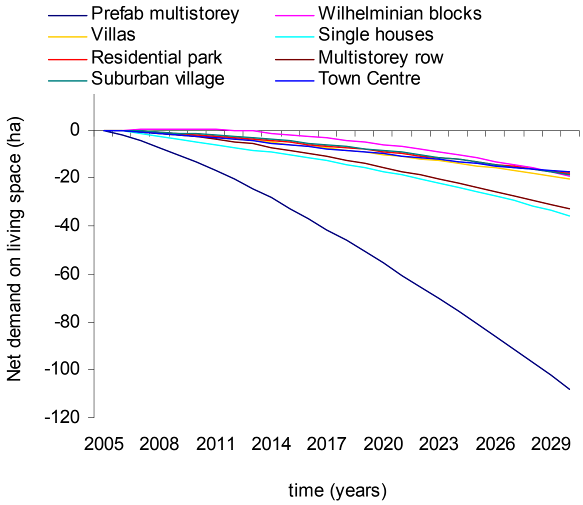


Figure 4. Development of the number of persons living in young and elderly single households compared to those living in family households with children. Blue = shrinkage; grey = baseline; red = growth.



Shrinkage



Growth

Figure 5. Net demand-supply-relation on living space in the different urban structure types for the growth and shrinkage scenarios.

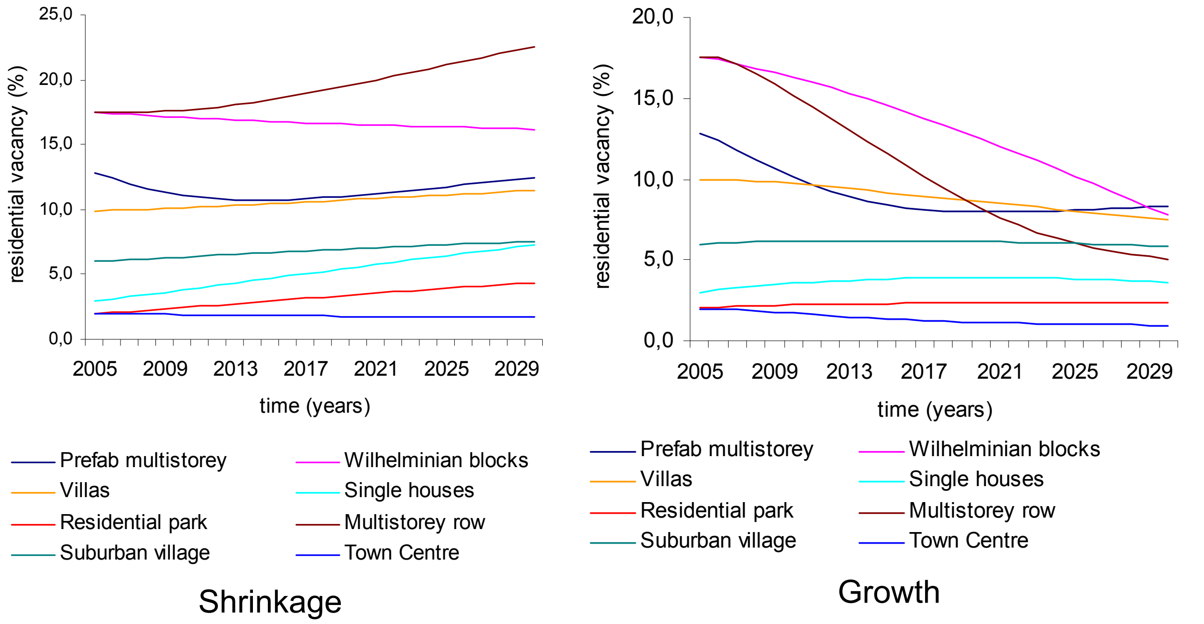


Figure 6. Residential vacancy in the 8 urban structure types for the growth and the shrinkage scenarios.

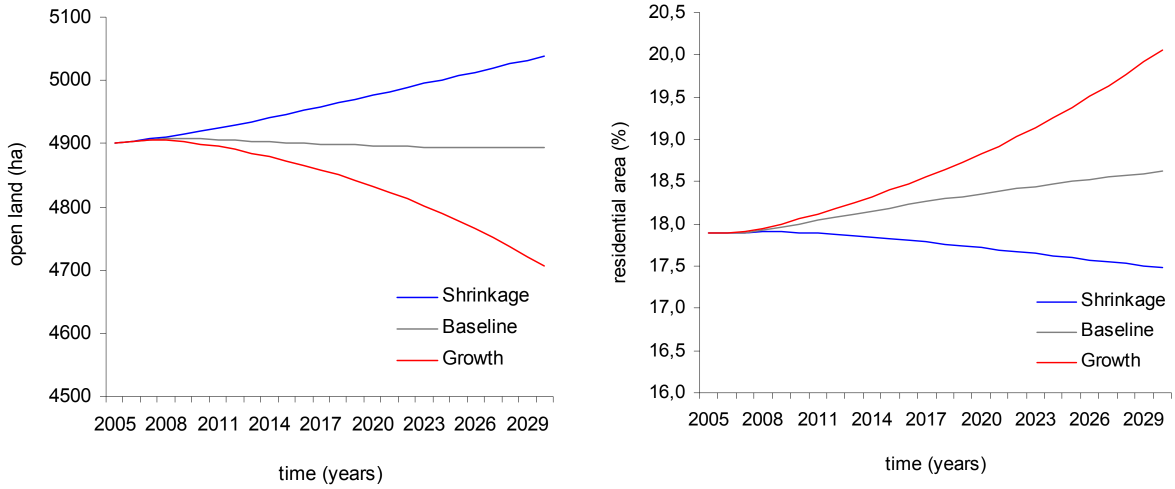


Figure 7. Development of open land and residential area in the three scenarios: baseline, growth and shrinkage.

	Population	Singles	Vacancy	Resid. Land	Open Land
Growth	↗	↗	↘	↗	↘
Baseline	↗	↗	→	→	→
Shrinkage	↘	↘	↗	→	→

Figure 8. Major trends of the growth, baseline and shrinkage scenarios.

Appendix: supplementary material

Description of variables

Population

Pop class, $P_i(t)$	Population of the study area classified into *i* age cohorts
Ageing, $A_i(t)$	Cohort transition rate for cohort *i*
Fertility, $F_i(t)$	Fertility rate per cohort *i*
Mortality, $\mu_i(t)$	Mortality rate (probability of dying) per cohort *i*
In-mig, $I_i(t)$	Persons moving into the study area, classified into *i* age cohorts
Out-mig, $O_i(t)$	Persons leaving the study area, classified into *i* age cohorts

Household types

Household types, $HHT_k(t)$	Population number per HHT *k*
Mean income, $MI_k(t)$	Annual man income per HHT *k*
Distribution matrix, $M_{ki}(t)$	Transition matrix for HHT *k* out of age cohorts *i*
Change of M, N_m	Change of distribution matrix $M_{ki}(t)$
Social matrix, $SoM_{kk}(t)$	Attributable preference among two HHT *k* regarding vicinity
Residential attractiveness, $RA_{kj}(t)$	Probability of housing decision per HHT *k* and UST *j*, taken into account preferences of *k* and conditions of *j*
Valuations ($CtV_k(t)$, $SuV_k(t)$, $CV_k(t)$, $BSV_k(t)$, $CrV_k(t)$, $EV_k(t)$, $GV_k(t)$, $SoV_k(t)$)	Basic preference of each HHT for *n* (see a.x., p.40) per HHT without considering the household income
Preference valuation, $PV_n(t)$	Weighting parameter for the preference variables *n* depending on the middle income $MI_k(t)$
Preferences ($BSP_k(t)$, $CP_k(t)$, $CrP_k(t)$, $CtP_k(t)$, $EP_k(t)$, $GP_k(t)$, $SoP_k(t)$, $SuP_k(t)$)	Attributable preference of variable *n* for each HHT *k*

Real estate, housing area of UST

Demand_HHT, $DP_{jk}(t)$	Number of demanding persons per HHT *k* and UST *j*
Demand living space, $DLS_{jk}(t)$	Demand of living space per HHT *k* and UST *j* in hectare
Supply _HHT, $SP_{jk}(t)$	*De facto* number of persons living in UST *j* per HHT *k*
Supply living space, $SLS_{jk}(t)$	*De facto* use of living space per HHT *k* and UST *j* in hectare, excluding vacancies
Vacancy, $V_j(t)$	Vacant living space per UST *j* in hectare
Space Supply, $SS(t)$	Total open land (available, potential building land) in hectare
Construction, $co_j(t)$	New built-up living space per UST *j* in hectare
Deflation, $df_j(t)$	New vacant living space per UST *j* in hectare
Reuse, $ru_j(t)$	New revitalised vacancies per UST *j* in hectare
Demolition, $dl_j(t)$	New pulled-down vacant living space per UST *j* in hectare
Demand residential area, $DRA_j(t)$	Potential (demand on) residential area (building area and plot area) UST *j* in hectare
Supply residential area,	*De facto* residential area (building area & plot area), excluding

$SRA_j(t)$	vacancies per UST *i* in hectare
Total living space, $TLS_j(t)$	*De facto* use of total living space per HHT *k* and UST *i* in hectare, including vacancies
Total residential area, $TRA_j(t)$	*De facto* residential area building area & plot area per UST *i* in hectare, including vacancies
Building area, $BA_j(t)$	Total building area for each UST *i* in hectare
Rates ($GR_j(t)$, $ER_j(t)$, $CrR_j(t)$, $BSR_j(t)$, $CR_j(t)$)	Change rates of UST *i* regarding preference variables *n* (see a.x., p.40)
Conditions ($BSC_j(t)$, $CC_j(t)$, $CrC_j(t)$, $EC_j(t)$, $GC_j(t)$, $SoC_{jk}(t)$, $SuC_j(t)$)	Normalised condition of each UST *i* regarding preference variables *n*
Building State, $BS_j(t)$	State of restoration per UST *i* (means of each UST)
Centrality, Ct_j	Weighted distance to centre per UST *i* (const. values)
Cost, $C_j(t)$	Average rent per UST *i* in Euro
Crime, $Cr_j(t)$	Number of delicts per UST *i*
Education, $E_j(t)$	Number of institutions of education (schools, kindergartens) per UST *i*
Green, $G_j(t)$	Green space per person and UST *i* (park density, lot green)
Surroundings, Su_j	Living settings in neighbourhoods of UST *i*, gained by different describing parameters, e.g., cleanness, noise (const. value)

Collection of formula

Indices

t = time $t \in R,\ t > 0$

i = population cohorts

$$i = \begin{pmatrix} 0-15 \\ 16-25 \\ 26-35 \\ 36-45 \\ 46-55 \\ 56-65 \\ 66-75 \\ 75+ \end{pmatrix} \qquad x \in N, x \le 8$$

k = household types (HHT)

$$k = \begin{pmatrix} young\ one\text{-}person\ household\ \ (<45\ years) \\ elderly\ one\text{-}person\ household\ \ (>45\ years) \\ young\ cohabitation\ household\ \ (<45\ years) \\ elderly\ cohabitation\ household\ \ (>45\ years) \\ family\ with\ dependent\ children\ \ <18\ years \\ \sin gle\ parent\ with\ dependent\ children\ \ <18\ years \\ unrelated\ adults\ \ (flat\text{-}sharers)\ \ <45\ years \end{pmatrix}$$

$$k \in N, k \le 7$$

j = urban structure types (UST)

$$j = \begin{pmatrix} prefabricated\ multiy\text{-}storey \\ Wilhelminian\ blocks \\ villas \\ single\ (one/two\ family)\ houses \\ residential\ park\ since\ 1990 \\ multi\text{-}storey\ row \\ suburban\ village \\ city\ centre \end{pmatrix} \qquad j \in N, i \leq 8$$

n = characterisation variables

$$n = \begin{pmatrix} centrality \\ housing\ surrounding \\ housing\ cost \\ building\ state \\ crime\ rate \\ education\ facilities \\ green\ supply \\ social\ neighbourhood \end{pmatrix} \qquad n \in N, l \leq 8$$

m = change rate (HHT-Matrix) $m \in N, m \leq 4$

l = parameter of rates $l \in N, l \leq 4$

Population

Ageing, $A_i(t)$

$$A_i = \frac{1}{10} \qquad i \neq 1$$

$$A_1 = \frac{1}{15} \qquad i = 1$$

In-mig, $I_i(t)$

$$I_i(t) = f_I\left(\left[Gauss\right], TI_i, SS\right) \qquad \frac{\partial I}{\partial TI} \geq 0,\ \frac{\partial I}{\partial SS} \geq 0$$

$$I_i = \left(N_{iI}(\mu_i, \sigma_i) + TI_i\right) \cdot \left(1 - \frac{SS_{T2}}{SS}\right) \qquad N = Gauss\text{-}distribution$$

$$\mu_i = \left[1690;\ 7553;\ 5756;\ 2558;\ 1416;\ 1096;\ 822;\ 822\right] \qquad \mu_i = mean$$

$$\sigma i = \left[100;\ 150;\ 150;\ 100;\ 100;\ 100;\ 50;\ 50\right] \qquad \sigma_i = standard\ deviation$$

Out-mig, $O_i(t)$

$$O_i(t) = f_O\left(\left[Gauss\right], TO_i, SS\right) \qquad \frac{\partial O}{\partial TO} \geq 0,\ \frac{\partial O}{\partial SS} \leq 0$$

$$O_i = \left(N_{iO}(\mu_i, \sigma_i) + TO_i\right) \cdot \left(1 - \frac{SS_{T2}}{SS}\right)^{-1} \qquad N = Gauss\text{-}distribution$$

$$\mu_i = \left[2185;\ 4369;\ 5248;\ 3386;\ 2130;\ 1420;\ 993;\ 993\right] \qquad \mu_i = mean$$

$$\sigma i = \left[100;\ 150;\ 150;\ 100;\ 100;\ 100;\ 50;\ 50\right] \qquad \sigma_i = standard\ deviation$$

Household types

Mean income, $MI_k(t)$

$$MI_k = N_{kMI}(\mu_k, \sigma_k) \qquad N = Gauss\text{-}distribution$$

$$\mu_k = mi_k = \left[920; 970; 1892; 1708; 2226; 1283; 844\right] \qquad \mu_k = mean$$

$\sigma_k = 50$ $\sigma_k = standard\ deviation$

Distribution matrix, $D_{ki}(t)$

if $k = 1,2,6$ then $(1 + N_m)$ if $k = 3,4,5$ then $(1 - N_m)$

if $k = 1,2\ then\ m = 1$ if $k = 3,4\ then\ m = 2$

if $k = 5\ then\ m = 3$ if $k = 6\ then\ m = 4$

Preference variables, such as *Cost Preference* $CP_k(t)$ are determined by their valuation (see below) and their ratio of the summed preference for each *k*

Centrality valuation, $CtV_k(t)$

$$CtV_k = [0;\ 0{,}1283;\ 0{,}1516;\ 0{,}1272;\ 0{,}0749;\ 0{,}1190;\ 0{,}2700] \cdot PV_1$$

Surroundings valuation, $SuV_k(t)$

$$SuV_k = [0; 0{,}1130; 0{,}1220; 0{,}1674; 0{,}2561; 0{,}1712; 0{,}0137] \cdot PV_2$$

Cost valuation, $CV_k(t)$

$$CV_k = [0{,}3263;\ 0{,}1819;\ 0{,}1381;\ 0{,}0647;\ 0;\ 0{,}0986;\ 0{,}0813] \cdot PV_3$$

Building state valuation, $BSV_k(t)$

$$BSV_k = [0;\ 0{,}1306;\ 0{,}1691;\ 0{,}1193;\ 0{,}0847;\ 0{,}1303;\ 0{,}2265] \cdot PV_4$$

Crime valuation, $CrV_k(t)$

$$CrV_k = [0{,}0947;\ 0{,}1279;\ 0{,}0841;\ 0{,}1529;\ 0{,}2722;\ 0{,}1347;\ 0] \cdot PV_5$$

Education valuation, $EV_k(t)$

$$EV_k = [0{,}3149;\ 0{,}1198;\ 0{,}1101;\ 0{,}0846;\ 0;\ 0{,}0770;\ 0{,}2101] \cdot PV_6$$

Green valuation, $GV_k(t)$

$$GV_k = [0;\ 0{,}1062;\ 0{,}0750;\ 0{,}1797;\ 0{,}3122;\ 0{,}1262;\ 0{,}0684] \cdot PV_7$$

Social valuation, $SoV_k(t)$

$$SoV_k = [0{,}2642;\ 0{,}0923;\ 0{,}1502;\ 0{,}1044;\ 0;\ 0{,}1430;\ 0{,}1300] \cdot PV_8$$

Social matrix, $SoM_{kk}(t)$

$$SoM_{kk} = SoM_{kk}(0) \cdot SoP_k$$

Preference valuation, $PV_n(t)$ if $MI_k > mi_k$ then $PV_n = [2;\ 3;\ 6;\ 3;\ 4;\ 2;\ 3;\ 3]$

if $MI_k < mi_k$ then $PV_n = [1;\ 2;\ 8;\ 2;\ 3;\ 1;\ 2;\ 2]$

$mi_k = [920;970;1892;1708;2226;1283;844]$ $mi_k = mean$

Real estate, housing area of UST

Vacancy, $V_j(t)$ $$\frac{dV_j}{dt} = \sum_{k=1}^{7} df_{jk} - \sum_{k=1}^{7} ru_{jk} - dl_j \qquad V_i > 0$$

Demolition, $dl_j(t)$ $dl_j = DLS_j(t-1) \cdot DlR_j$ (analogous Deflation)

Construction, $co_j(t)$ $co_j = DLS_j \cdot CoR_j$ (analogous Reuse)

Supply _HHT, $SP_{jk}(t)$ $$SP_{jk} = \frac{SLS_{jk} \cdot 10000}{LSC_k}$$

Supply residential area, $SRA_j(t)$ $$SRA_j = \frac{SLS_j \cdot FSM}{FSD_j}$$

Demand residential area, $DRA_j(t)$ $$DRA_j = \frac{DLS_j \cdot FSM}{FSD_j}$$

Total living space, $TLS_j(t)$ $$TLS_j = V_j + SLS_j$$

Total residential area, $TRA_j(t)$ $$TRA_j = \frac{TLS_j \cdot FSM}{FSD_j}$$

Building area, $BA_j(t)$ $$BA_j = \frac{TLS_j}{St_j}$$

Space Supply, $SS(t)$ $$\frac{\mathrm{d}SS}{\mathrm{d}t} = dl_j - \sum_{k=1}^{7} co_{jk}$$

UST-valuing conditions per UST (green supply, crime rate) are calculated by the difference from the previous year as a ratio of the sum of each condition variable at time *t*

Described UST variables are calculated by multiplying their amount at time *t* and their respective rates (see below)

Green, $G_j(t)$ $$\frac{dG}{dt} = GR \cdot G$$ (analogous crime, education, green)

Green rate, $GR_j(t)$ $$GR_j(t) = f_{GR}(dl_j, co_j, SP_j)$$ $$\frac{\partial GR_j}{\partial dl_j} \geq 0, \quad \frac{\partial GR_j}{\partial co_j} \leq 0, \quad \frac{\partial GR_j}{\partial SP_j} \leq 0$$

$$GR_j = \frac{\sum_{k=1}^{7} dl_{jk} - \sum_{k=1}^{7} co_{jk}}{\sum_{k=1}^{7} SP_{jk}} \cdot GPa$$

Education rate, $ER_j(t)$ $$ER_j(t) = f_{ER}(PE)$$ $$\frac{\mathrm{d}ER_j}{\mathrm{d}PE_j} \geq 0$$

$$ER_j = \left(\frac{PE_j}{PE_j(t-dt)} - 1 \right) \cdot EPa$$

Crime rate, $CrR_j(t)$ $$CrR_j(t) = f_{CrR}\left(\left[SP_j / SRA_j \right], SV_j \right)$$ $$\frac{\partial CrR_j}{\partial \left[SP_j / SRA_j \right]} \geq 0, \quad \frac{\partial CrR_j}{\partial SV_j} \geq 0$$

$$CrR_j = \left(\left(\frac{\sum_{k=1}^{7} SP_{jk}}{SRA_j} \right) \cdot \left(\frac{\sum_{k=1}^{7} SP_{jk}\left(t-dt\right)}{SRA_j(t-dt)} \right)^{-1} - 1 \right) \cdot 0.5 + \left(\frac{SV_j}{SV_j\left(t-dt\right)} - 1 \right) \cdot 0.5 \cdot CrPa$$

$$-0.1 < CrR_j < 0,1$$

Building state rate, $BSR_j(t)$ $$BSR_j(t) = f_{BSR}(DLS)$$ $$\frac{\mathrm{d}BSR_j}{\mathrm{d}DLS_j} \geq 0$$

$$\frac{\mathrm{d}BSR_j}{\mathrm{d}t} = \left(\frac{DLS_j}{DLS_j(t-dt)} - 1 \right) \cdot \sum_{j=1}^{8} \left(\frac{DLS_j}{DLS_j(t-dt)} - 1 \right)^{-1}$$

Cost rate, $CR_j(t)$ $\quad CR_j(t) = f_{BSR}(DLS_j, SLS_j)$ $\quad \frac{\partial CR_j}{\partial DLS_j} \geq 0$, $\frac{\partial CR_j}{\partial SLS_j} \leq 0$

$$CR_i = \frac{DLS_i - SLS_i}{SLS_i} \cdot CPa$$

Initials and parameter

Pop class $\quad P_i(0) = (57113;\ 70064;\ 83662;\ 76672;\ 62729;\ 77499;\ 49088;\ 38077)$

Fertility $\quad F_i(0) = (0; 0.015; 0.027; 0,0036; 0; 0; 0; 0)$

Mortality $\quad M_i(0) = (0.002; 0; 0; 0; 0; 0.005; 0.009; 0.08)$

Vacancy $\quad V_j(0) = [0.10;\ 0.38;\ 0.15;\ 0.03;\ 0.03;\ 0.15;\ 0.08;\ 0.02]$

City area $\quad CA = 26761$

Space supply $\quad SS(0) = 1960 \cdot 2.5$

Supply living space $\quad SLS_j(0) = (267.2; 657.6; 886.6; 314.8; 77.2; 207.2; 205.9; 141.3)$

Reuse rate $\quad RR_j(0) = (0;\ -0.095;\ -0.095;\ 0;\ 0;\ 0;\ -0.025;\ 0)$

Deflation rate $\quad VR_j(0) = (0.023;\ 0.001;\ 0,001;\ 0.0021;\ 0.001;\ 0.0077;\ 0.001;\ 0.001)$

Demolition rate

$$DlR_j(0) = (0.011;\ 0.00114;\ 0.00114;\ 0.00015;\ 0.00008;\ 0.00114;\ 0.00114;\ 0.0001)$$

Construction rate $\quad CoR_j(0) = (0;\ 0.0024;\ 0.002;\ 0.0332;\ 0.01;\ 0.0005;\ 0.0005;\ 0.0005)$

Green area $\quad G_j(0) = (2.43;\ 0.92;\ 4.09;\ 8.81;\ 3.62;\ 2.26;\ 3.61;\ 0.59)$

Education $\quad E_j(0) = (0.17;\ 0.13;\ 0.12;\ 0.05;\ 0.06;\ 0.14;\ 0.07;\ 0)$

Crime $\quad Cr_j(0) = (130;\ 159;\ 155;\ 84;\ 90;\ 100;\ 106;\ 250)$

Building state $\quad BS_j(0) = (0.073;\ 0.112;\ 0.165;\ 0.097;\ 0.100;\ 0.134;\ 0.099;\ 0.220)$

Cost $\quad C_j(0) = (5;\ 5.5;\ 6.25;\ 6.5;\ 6.25;\ 5;\ 5.5;\ 6.5)$

Centrality $\quad Ct_j = (0.064;\ 0.127;\ 0.175;\ 0.090;\ 0.070;\ 0.089;\ 0.075;\ 0.309)$

Surroundings $\quad Su_j = (0.05;\ 0.104;\ 0.114;\ 0.127;\ 0.145;\ 0.142;\ 0.142;\ 0.112)$

Distribution matrix Pop_HHT

$$D_{ki}(0) = \begin{pmatrix} DM_{11} & \dots & DM_{k8} \\ \vdots & \ddots & \vdots \\ DM_{7x} & \cdots & DM_{kx} \end{pmatrix} = \begin{pmatrix} 0 & 0.21 & 0.21 & 0.15 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.25 & 0.25 & 0.4 & 0.45 \\ 0 & 0.15 & 0.17 & 0.3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.3 & 0.63 & 0.5 & 0.25 \\ 0.7 & 0.25 & 0.3 & 0.35 & 0.35 & 0.09 & 0 & 0 \\ 0.3 & 0.15 & 0.12 & 0.13 & 0.1 & 0.03 & 0 & 0 \\ 0 & 0.24 & 0.2 & 0.07 & 0 & 0 & 0.1 & 0.3 \end{pmatrix}$$

Social matrix

$$SoM_{kk} = \begin{pmatrix} SoM_{11} & \dots & SoM_{7k} \\ \vdots & \ddots & \vdots \\ SoM_{k7} & \cdots & SoM_{kk} \end{pmatrix} = \begin{pmatrix} 0.048 & 0.238 & 0.048 & 0.238 & 0.190 & 0.190 & 0.048 \\ 0.217 & 0.043 & 0.217 & 0.043 & 0.174 & 0.174 & 0.130 \\ 0.048 & 0.238 & 0.048 & 0.238 & 0.190 & 0.190 & 0.048 \\ 0.111 & 0.111 & 0.111 & 0.111 & 0.222 & 0.222 & 0.111 \\ 0.111 & 0.111 & 0.111 & 0.111 & 0.222 & 0.222 & 0.111 \\ 0.235 & 0.059 & 0.235 & 0.059 & 0.059 & 0.059 & 0.294 \\ 0.208 & 0.042 & 0.208 & 0.042 & 0.167 & 0.167 & 0.167 \end{pmatrix}$$

Distribution matrix UST_HHT

$$ID_{jk} = \begin{pmatrix} ID_{11} & \cdots & ID_{7i} \\ \vdots & \ddots & \vdots \\ ID_{k8} & \cdots & ID_{ki} \end{pmatrix} = \begin{pmatrix} 0.197 & 0.255 & 0.099 & 0.140 & 0.176 & 0.088 & 0.045 \\ 0.188 & 0.179 & 0.086 & 0.193 & 0.130 & 0.098 & 0.126 \\ 0.012 & 0.092 & 0.175 & 0.215 & 0.264 & 0.085 & 0.158 \\ 0 & 0.147 & 0.035 & 0.218 & 0.479 & 0.091 & 0.029 \\ 0.032 & 0.101 & 0.096 & 0.189 & 0.404 & 0.160 & 0.019 \\ 0.150 & 0.256 & 0.130 & 0.136 & 0.146 & 0.120 & 0.062 \\ 0.147 & 0.207 & 0.100 & 0.199 & 0.206 & 0.114 & 0.027 \\ 0.015 & 0.268 & 0.127 & 0.176 & 0.215 & 0.127 & 0.072 \end{pmatrix}$$

Space supply threshold	$SS_{T1} = 50$; $SS_{T2} = 150$, $SS_{T3} = 800$
Fertility trend	$FT_2 = -0.0003 \cdot Log10(t) + 0.0005$
	$FT_3 = -0.0004 \cdot Log10(t) + 0.0009$
	$FT_4 = -0.00026 \cdot Log10(t) + 0.0007$
	$FT_{1,5,6,7,8} = 0$
Mortality trend	$MT_i = 0.0026 \cdot Log10(t) - 0.0124$
In-mig trend	$TI_1 = 77.36 \cdot t^{(-1.0673)}$, $TI_2 = 313.6 \cdot t^{(-1.0673)}$, $TI_3 = 263.4 \cdot t^{(-1.0673)}$, $TI_4 = 117.1 \cdot t^{(-1.0673)}$, $TI_5 = 64.8 \cdot t^{(-1.0673)}$, $TI_6 = 50.2 \cdot t^{(-1.0673)}$, $TI_7 = 37.6 \cdot t^{(-1.0673)}$, $TI_8 = 37.6 \cdot t^{(-1.0673)}$
Out-mig trend	$TO_i = TI_i \cdot (-1)$
Change distribution matrix	$N_m = [0.01;\ 0.01;\ 0.01;\ 0.005]$
Living space consumption	$LSC_k = [54;\ 54;\ 37,5;\ 35;\ 31;\ 35;\ 37]$
Storey	$St_j = [8;\ 4.2;\ 3.2;\ 2;\ 4.5;\ 5.5;\ 3.4;\ 5.4]$
Floor space multiplier	$FSM = 1.25$
Floor space density	$FSD_j = [1.1;\ 1.6;\ 0.6;\ 0.2;\ 0.7;\ 0.7;\ 0.4;\ 2.7]$
Green parameter	$GPa = 1000$
Education parameter	$EPa = 0.5$
Crime parameter	$CrPa = 0.4$
Building state parameter	$BSPa = 1$
Cost parameter	$CPa = 0.05$

		2005	2010	2015	2020	2025	2030
Scenario “Shrinkage”							
Inhabited residential area in hectare	town centre	11,0	11.6	12.1	12.5	12.9	13.2
	Wilhelminian-era old built-up blocks	728.4	726.7	722.9	717.8	712.2	706.5
	multi-storey row housing estates	429.6	427.6	420.6	410.5	399.5	388.4
	prefab multi-storey housing estates	308.7	295.1	276.3	255.5	234.8	215.1
	villas	186.5	188.7	189.2	188.7	187.8	186.7
	residential parks	145.3	146.5	146.2	145.5	144.8	144.4
	single houses	2590.4	2590.4	2575.8	2556.0	2533.9	2510.5
	suburban villages	498.2	499.2	497.5	494.6	491.2	487.8
Total vacancy in %	in %	12.3	12.1	12.3	12.6	13.0	13.3
Total residential area plus vacancy in hectare	town centre	11.3	11.9	12.3	12.8	13.1	13.4
	Wilhelminian-era old built-up blocks	883.0	876.4	868.6	860.1	851.5	842.9
	multi-storey row housing estates	521.1	519.3	515.8	511.4	506.6	501.7
	prefab multi-storey housing estates	354.0	332.1	309.6	287.5	266.1	245.8
	villas	207.0	210.0	211.2	211.5	211.3	210.9
	residential parks	148.3	150.1	150.7	150.8	150.8	150.9
	single houses	2670.5	2692.8	2702.5	2706.9	2708.5	2708.0
	suburban villages	529.9	533.0	533.2	531.9	529.9	527.5
Open Area	in hectare	4900.0	4919.0	4946.0	4976.1	5007.1	5038.1
Share residential area	in %	17.9	17.9	17.8	17.7	17.7	17.5

Table A2. Numbers of residential area, vacancy and remaining open land differentiated according to urban structural types for 2005-2030 for the baseline scenario.

		2005	2010	2015	2020	2025	2030
Scenario "Baseline"							
Inhabited residential area in hectare	town centre	11.0	12.5	14.6	16.6	18.2	19.3
	Wilhelminian-era old built-up blocks	728.4	730.7	735.9	742.8	750.1	757.3
	multi-storey row housing estates	429.6	435.3	447.1	460.5	473.7	486.0
	prefab multi-storey housing estates	308.7	300.0	289.1	274.6	258.1	240.6
	villas	186.5	191.8	200.5	208.7	215.9	222.1
	residential parks	145.3	147.6	152.2	156.5	160.1	163.1
	single houses	2590.4	2612.9	2646.6	2670.3	2688.8	2704.2
	suburban villages	498.2	502.8	512.4	522.7	532.5	541.6
Total vacancy	in %	12.3	11.6	10.8	10.2	9.6	9.1
Total residential area plus vacancy in hectare	town centre	11.3	12.7	14.8	16.8	18.4	19.5
	Wilhelminian-era old built-up blocks	883.0	877.0	871.7	867.3	863.1	859.1
	multi-storey row housing estates	521.1	520.3	522.6	526.9	532.5	539.0
	prefab multi-storey housing estates	354.0	335.2	318.3	301.7	284.6	266.9
	villas	207.0	212.8	222.0	230.6	238.3	245.0
	residential parks	148.3	151.0	156.1	160.9	165.0	168.5
	single houses	2670.5	2711.6	2760.2	2799.1	2832.7	2863.1
	suburban villages	529.9	536.3	547.5	559.1	570.2	580.4
Open Area	in hectare	4900.0	4906.7	4902.8	4896.6	4893.6	4893.1
Share residential area	in %	17.9	18.0	18.2	18.4	18.5	18.6

Table A3. Numbers of residential area, vacancy and remaining open land differentiated according to urban structural types for 2005-2030 for the growth scenario.

		2005	2010	2015	2020	2025	2030
Scenario "Growth"							
Inhabited residential area in hectare	town centre	11.0	13.0	16.5	20.3	24.1	28.6
	Wilhelminian-era old built-up blocks	728.4	734.0	745.3	760.9	779.1	800.3
	multi-storey row housing estates	429.6	441.3	466.1	498.2	534.9	574.3
	prefab multi-storey housing estates	308.7	303.2	296.4	285.9	273.5	260.4
	villas	186.5	195.0	211.0	230.1	252.5	277.9
	residential parks	145.3	149.3	158.8	170.8	185.6	202.7
	single houses	2590.4	2620.4	2673.4	2733.1	2812.7	2911.7
	suburban villages	498.2	506.8	525.9	551.0	581.4	617.0
Total vacancy	in %	12.3	11.2	9.8	8.5	7.2	6.0
Total residential area plus vacancy in hectare	town centre	11.3	13.2	16.7	20.5	24.4	28.9
	Wilhelminian-era old built-up blocks	883.0	876.9	872.3	869.3	867.6	867.5
	multi-storey row housing estates	521.1	520.4	527.0	542.6	569.1	604.9
	prefab multi-storey housing estates	354.0	337.3	323.6	310.7	297.5	284.1
	villas	207.0	216.0	232.3	251.8	274.5	300.4
	residential parks	148.3	152.7	162.6	174.9	190.0	207.6
	single houses	2670.5	2717.2	2779.7	2844.7	2924.8	3021.4
	suburban villages	529.9	540.2	560.7	586.9	618.5	655.3
Open Area	in hectare	4900.0	4899.0	4873.0	4832.9	4777.4	4705.5
Share residential area	in %	17.9	18.1	18.4	18.8	19.4	20.1

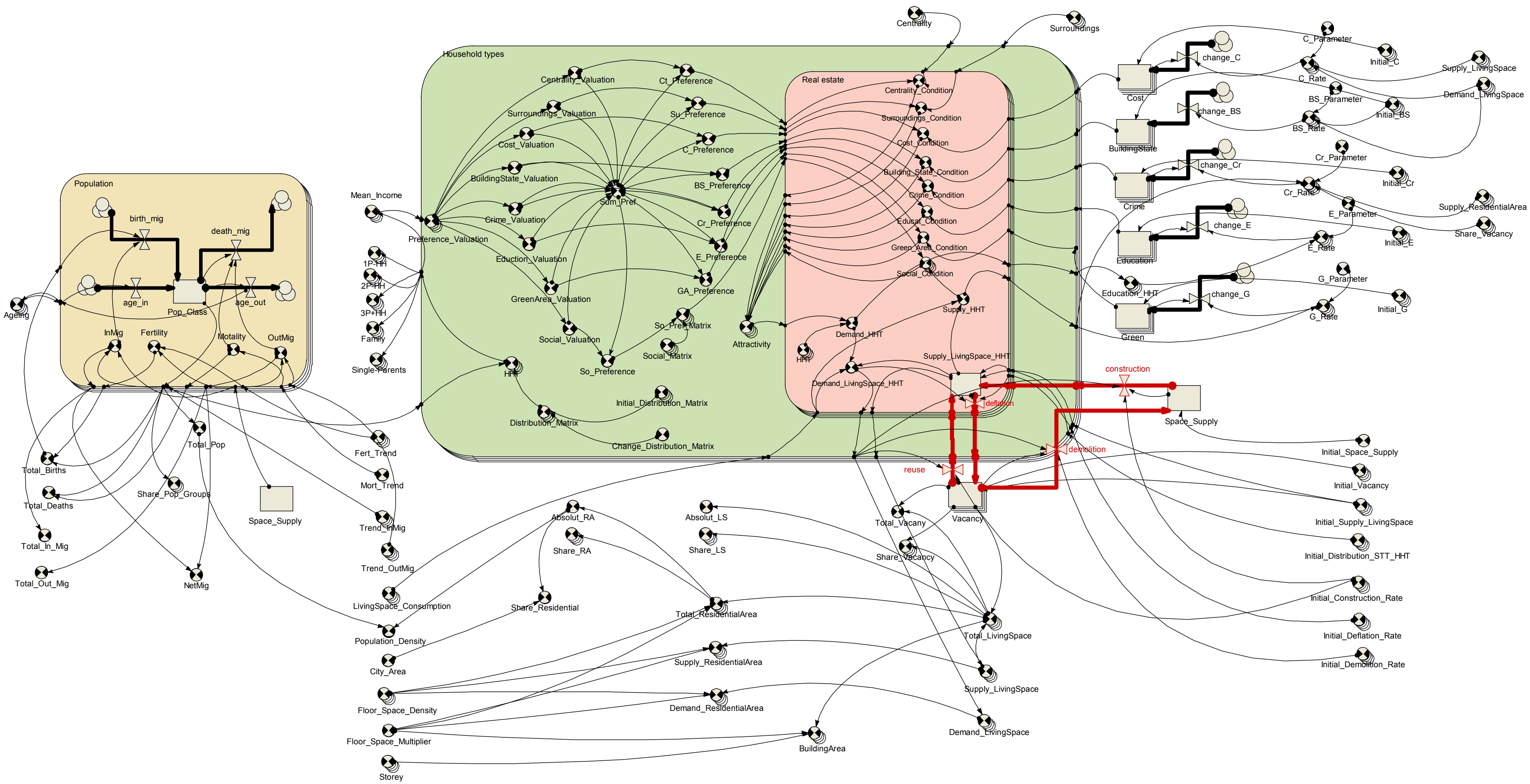
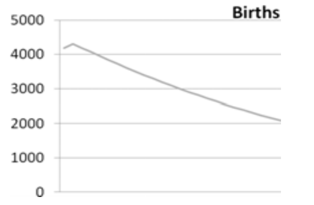
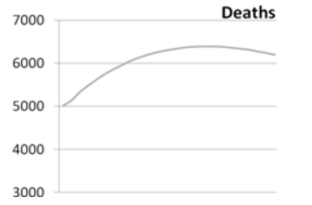
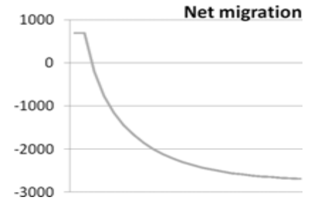
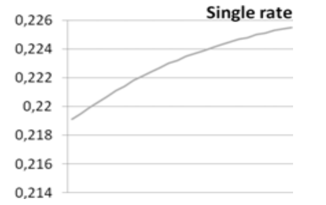
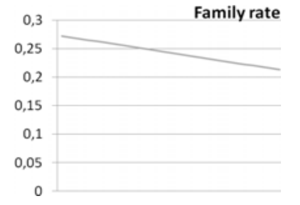
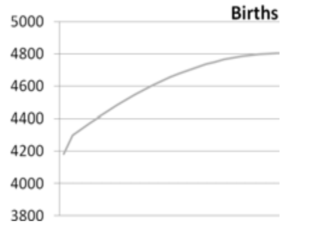
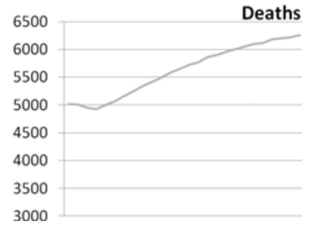
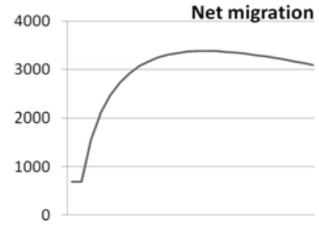
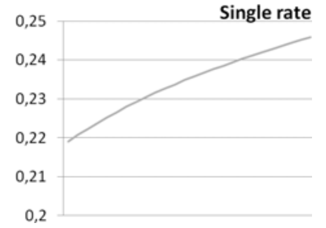
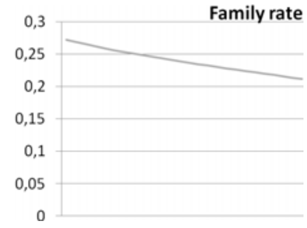
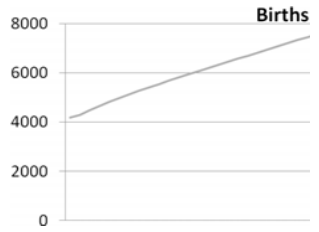
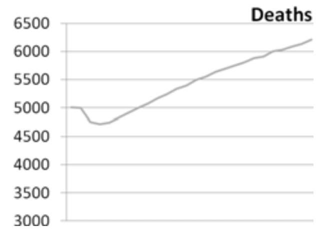
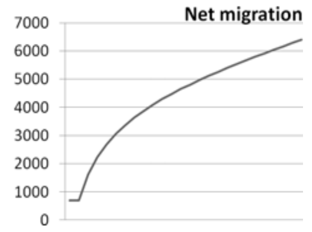
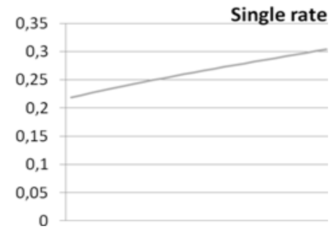
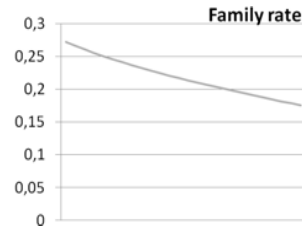


Figure A1. Detailed version of the model structure with all variables reported.

Scenario	Fertility	Mortality	Net migration	% Single households	% Families
Shrinkage					
Baseline					
Growth					

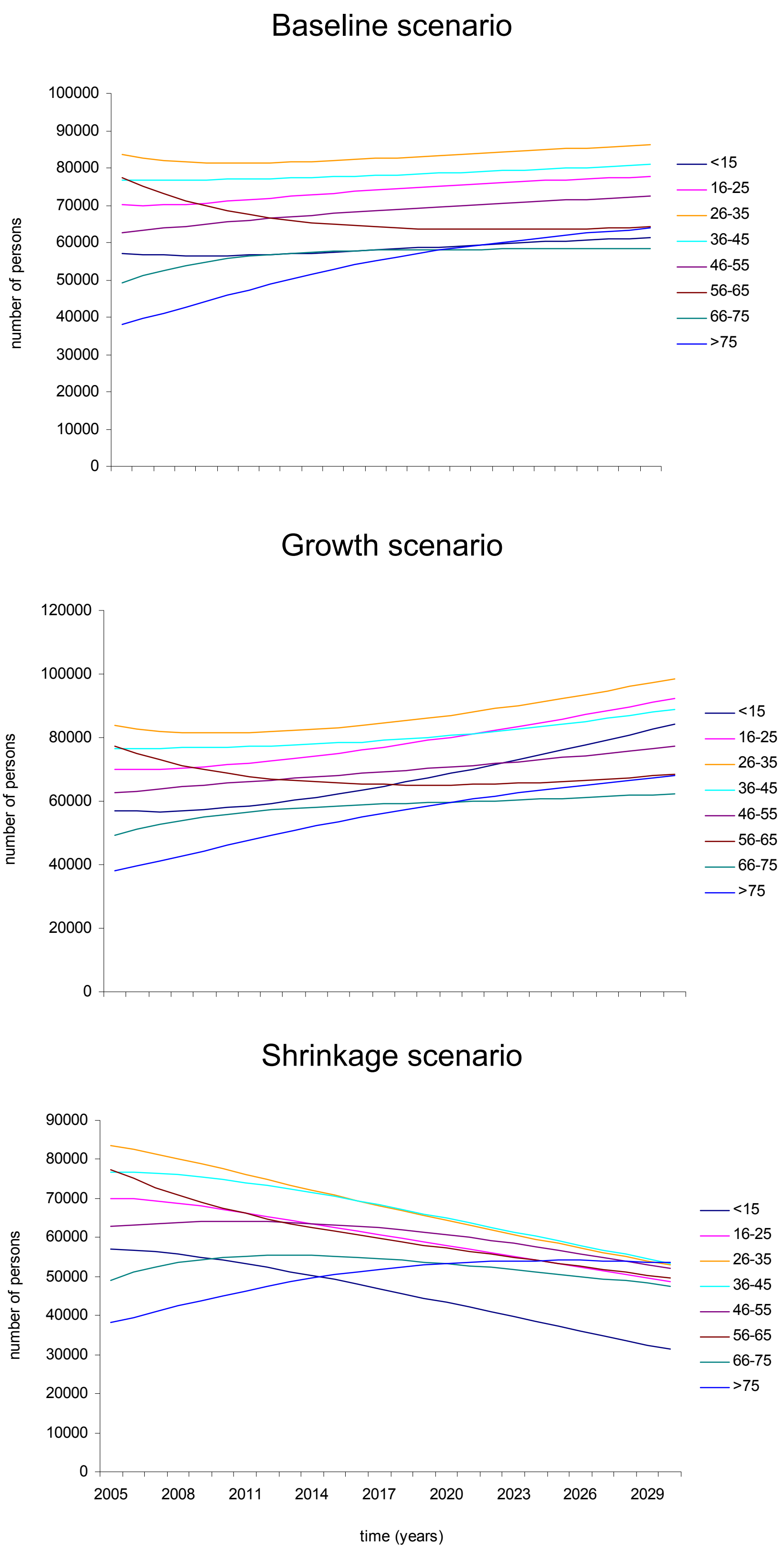


Figure A3. Development of the inhabitant age class structure for 2005-2030 for the baseline, growth and shrinkage scenarios.

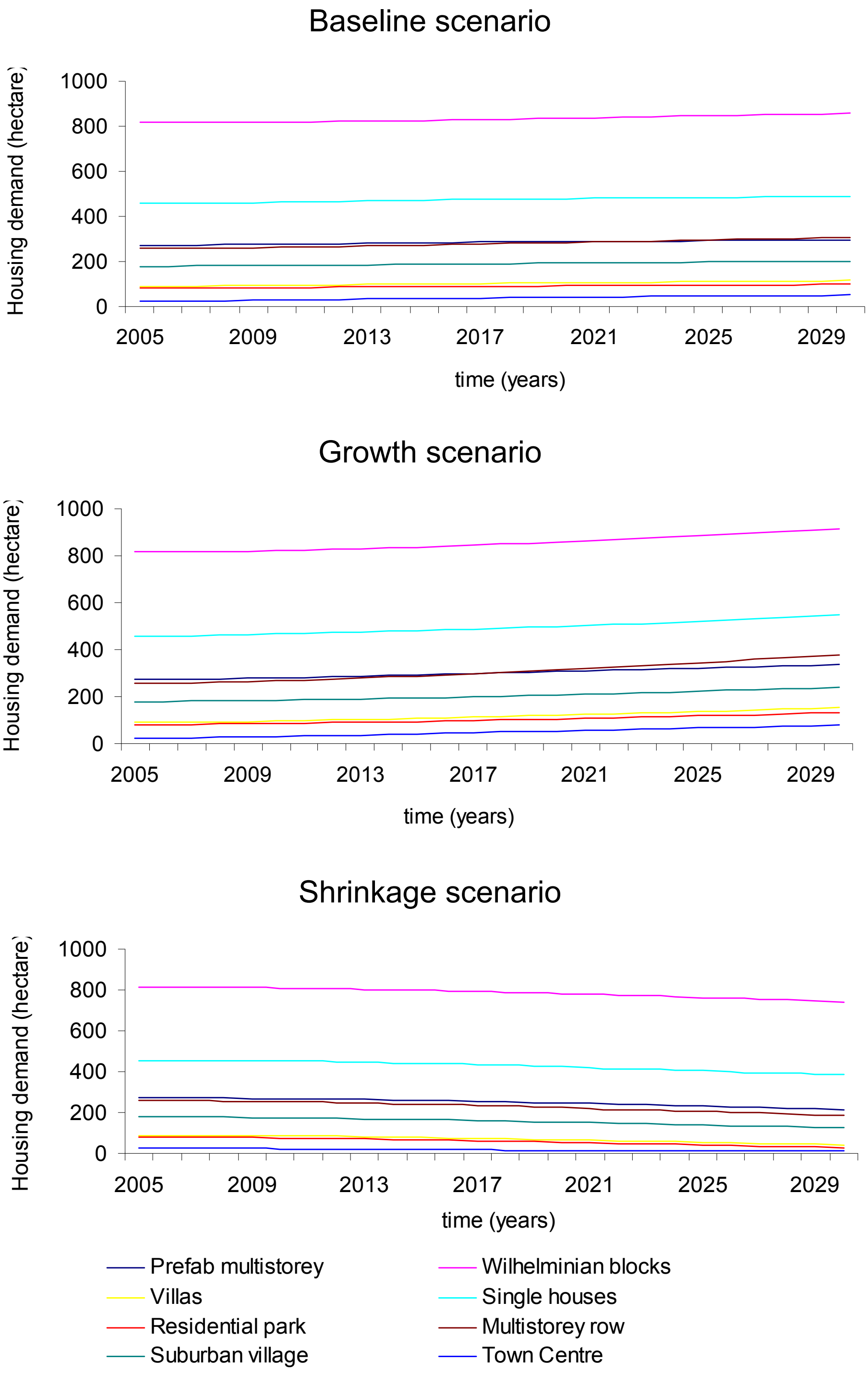


Figure A4. Housing demand for the baseline, growth and shrinkage scenarios.