Simulating residential land-use density

Eric Koomen[1], Bart Rijken[1,2] and Barry Zondag[2]

[1]Department of Spatial Economics/SPINlab, VU University Amsterdam, The Netherlands; [2]PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands;

Abstract Land-use simulation is an established part of the spatial planning process in the Netherlands. Existing modelling approaches, however, have hitherto focused on urban expansion and are less well equipped to assess the impact of expected changes within the existing urban fabric as a consequence of, for example, regional population decline. Urban restructuring and intensification are now considered to be prominent issues in land-use modelling. This calls for a change from an essentially land-cover type of approach common to most operational land-use model to a more object-oriented density-based approach. Our paper will discuss recent progress in describing current changes in urban densities and proposes an approach to incorporate this knowledge in a land-use simulation modelling framework. More specifically we will focus on capturing residential land-use density using highly detailed spatial datasets that describe the location of individual residences and residents.

1 Introduction

Models of land-use change have established themselves as geographical information and decision support systems as is documented in a wealth of literature (e.g. Geertman and Stillwell, 2009; Koomen et al., 2007; 2008). Such models are able to integrate geographical information on biophysical terrain conditions, infrastructure networks and occupation patterns with socio-economic scenarios to project future urbanisation patterns. A particularly successful example of a land-use model that has been applied to prepare and support spatial planning in the Netherland and neighbouring countries is Land Use Scanner (e.g. Hoymann, 2010; Koomen and Borsboom-van Beurden, 2011; te Linde et al., 2011). Recent Dutch applications, for example, concerned the preparation and evaluation of regional and national strategic spatial plans (Elings et al., 2011; Koomen et al., 2011b) and focussed mainly on urban expansion. Major spatial policy challenges for the future, however, relate to steering urban intensification in regions of urban growth and urban restructuring in regions of population decline (Kuijpers-Linde, 2011). We aim to prepare Land Use Scanner to deal with this type of policy issues. By incorporating temporal changes in the distribution and density of the major types of urban land use a truly four-dimensional decision support system is established that can be used to assess scenarios of urban development.

The current model distinguishes between different types of land use that only roughly correspond to underlying densities. Incorporating actual land-use density in the model calls for a redefinition of the way the demand for land is defined and used in the allocation process. As the strong regional variation in population development is currently a major policy issue and residential land use is the most important component of the urban fabric we focus on the incorporation of residential density in the land-use model.

2 Methodology

2.1 Modelling framework

Land use is the spatial representation of the complex interaction between natural and human systems. It is the result of the behaviour of many different types of actors such as households, companies and farmers. This behaviour is represented in the objects they manage and create (houses, farms etc.). Combinations of objects can be classified as land-use types that are usually named after the dominant objects in an area (e.g. residential land, arable farm land). The distinction of these three layers (actors, objects, land use) is central to our modelling framework.

Figure 1 shows the relation between the different layers and the way these are made operational in our modelling framework that combines the TigrisXL and Land Use Scanner model. The land-use and transport interaction model TigrisXL is used to simulate regional changes in numbers of actors and objects related to urban land use, based on trend-extrapolations or scenario-based assumptions on future conditions (Zondag and Geurs, 2011). Land Use Scanner is used simulate land-use patterns based on input from TigrisXL and other sector-specific models. The simulated land-use patterns are then used to describe impacts on various policy-related issues such as flood risk or urban sprawl based indicators calculation that are performed in Land Use Scanner itself or subsidiary models (Bubeck and Koomen, 2008; Ritsema van Eck and Koomen, 2008; Van der Hoeven et al., 2009).

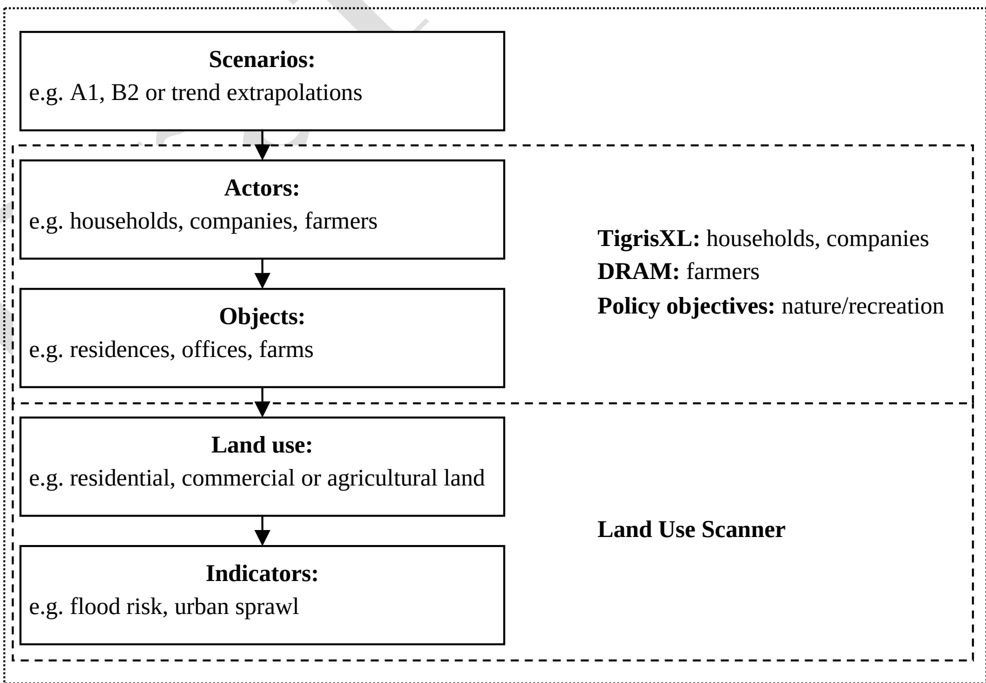

Figure 1 Modelling framework

Linking land use and density

Land-use models typically apply regularly shaped systems of grid cells to characterise the combinations of objects in an area into categories such as residential land, arable farm land. Obviously the relation between land-use type and dominant objects is stronger when the applied grid cells have a fine spatial resolution and get closer to the size of individual objects. Yet, land-use types also capture many objects that are associated with the main object. Residential land, for example, will typically also include local infrastructure, small public green spaces and facilities (shop, schools etc.) besides residences. Farm land will include occasional buildings (farms, stables) et cetera. Such additional elements are normally too small to be included in simulations of future land use and, more importantly, their spatial distribution is so closely related to the dominant object that distinguishing them is not useful. In our experience land-use simulation is especially helpful in indicating changes in spatial patterns and associated (environmental) impacts that relate to policy themes. Such simulations cannot and should not attempt to forecast the exact appearance of specific locations in future. Land-use types are thus always, to some degree, heterogeneous and information on the number of objects within a cell can help greatly in characterising them. This paper describes how residential density is added to our land-use model. More specifically following principles apply in our development of a new residential density module:

- Incorporate calculation of urban land demand within Land Use Scanner based on TigrisXL output;
- Use aggregate, predominantly residential area class that incorporates residences and related local facilities;
- Simulate changes in land use (e.g. urban extensions) using existing Land Use Scanner approach;
- Add information on underlying densities of actors and objects in base year (based on observations) and subsequent simulation years as additional grid-cell level layers to the model;
- Allow densities to change over time according to, for example, observed trends and scenario assumptions.

2.2 Model framework components

Tigris XL

Tigris XL is a so-called Land Use and Transport Interaction (LUTI) model, which uses the National Transport Model (LMS) of the Netherlands as its transport module (RAND Europe and Bureau Louter, 2006; Zondag, 2007).

The key characteristics of the Tigris XL model are:

- It is a dynamic land-use model simulating time steps of 1 year. This enables it to simulate path dependency and to analyse how the system evolves over time. Within its incremental structure the model uses partial equilibrium conditions, for example to match supply and demand within a year on the housing market.
- The module for choice of residential location has been statistically estimated, for six different household types, based on a large housing market survey (over 100,000 respondents). The module for choice of location of firms (represented as jobs in the model) has been estimated at municipality level for seven economic sectors on time-series data for the period 1986–2000. This enables the model to:
  - estimate the relationship between location of jobs and location of residents. Tigris XL does not use a pre-assumed hierarchical relationship but rather one that, based on estimation results, varies between economic sectors and household segments;
  - statistically estimate, based of revealed preference data, the influence of accessibility on the distribution of households and jobs.
- The land-use and transport system is simulated in Tigris XL in a set of linked modules addressing specific aspects of the systems (e.g. demography). The overall architecture determines the sequences of the modules and data exchanges between the modules. This allows flexibility to change or re-estimate specific modules without the need to change the whole framework.
- The land-use model operates in a way tailored to the National Transport model (LMS) of the Netherlands. The spatial detail of the land-use model is at the level of transport zones.
- The model has a three-layer structure, namely land, objects (such as dwellings) and activities (people, jobs).
- The land-market module in Tigris XL has different options to simulate the influence of government on spatial development. Depending on its settings it can simulate new urban development in three ways:
  - as a free-market development following the preferences of residents and firms. Location choices are only restricted by the lack of available land or possible spatial planning restrictions (such as nature areas);
  - as regulated development via designated locations and numbers of houses (in this case only the location choice of residents is simulated with the model); or
  - as an intermediate variant that takes development plans as a starting point but adjusts them within a certain range to actual market demand.

Tigris XL consists of five modules, which together address demography and spatial markets. Figure 2 presents an overview of the model and the main relationships between the modules. The model distinguishes two spatial-scale levels: the municipality level (approximately 450 regions) and local transport zones of the National Model System (LMS sub-zones; 1308 sub-zones cover the Netherlands).

Core modules in the model are the housing market and labour market modules. These account for the effect of changes in transport on residential or firm location behaviour and in this way link changes in the transport system to changes in land use. A land and real-estate module simulates supply constraints arising from the amount of available land, land-use policies and construction. The module defines different levels of government influence on spatial development, ranging from completely regulated towards free market, and various feedback loops between demand and supply are also available. A demographic module is included to simulate demographic changes at the local level. At the national level, the model's output is consistent with existing demographic and socio-economic forecasts for population, labour force, income levels and employment.

The demographic module addresses processes such as births, deaths and ageing of the population, as well as changes in the composition of households. It deals with persons by category (gender, age) as well as households by category (size, income, etc.). The demographic module operates at the local subzone level and also processes the spatial distribution of scenario-based international migration flows.

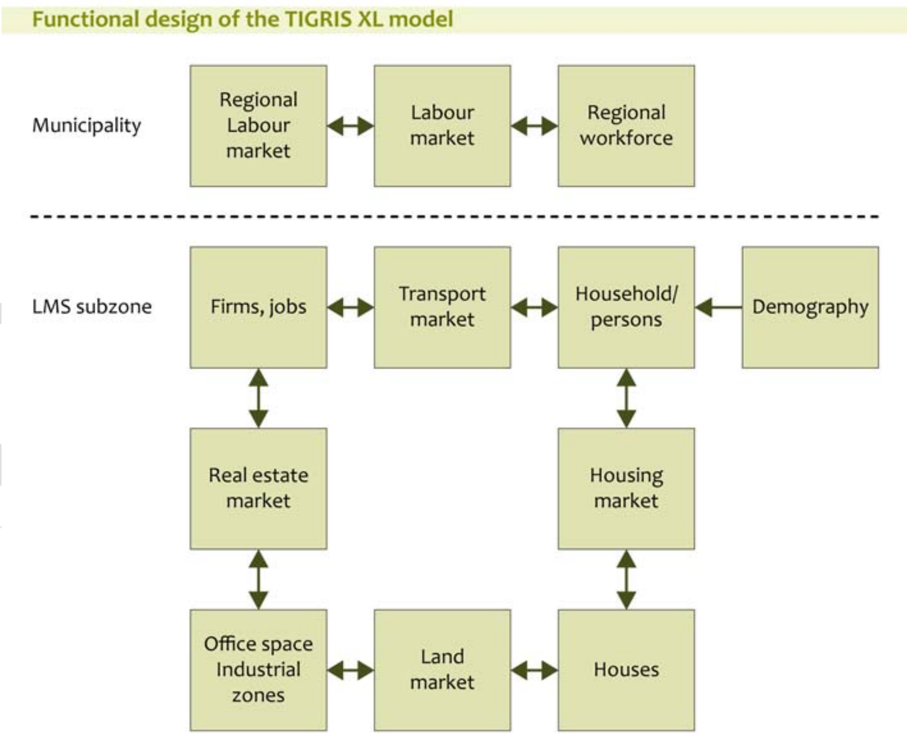

Figure 2: Functional design of the Tigris XL model (source: Zondag and Geurs, 2011).

Land Use Scanner

The basic structure of Land Use Scanner consists of a specification of regional demand for land, a definition of local suitability, an allocation module and resulting depictions of future land use (Figure 3). The model has been described extensively elsewhere (Koomen et al., 2011; Loonen and Koomen, 2009) so only a short description is provided in this subsection.

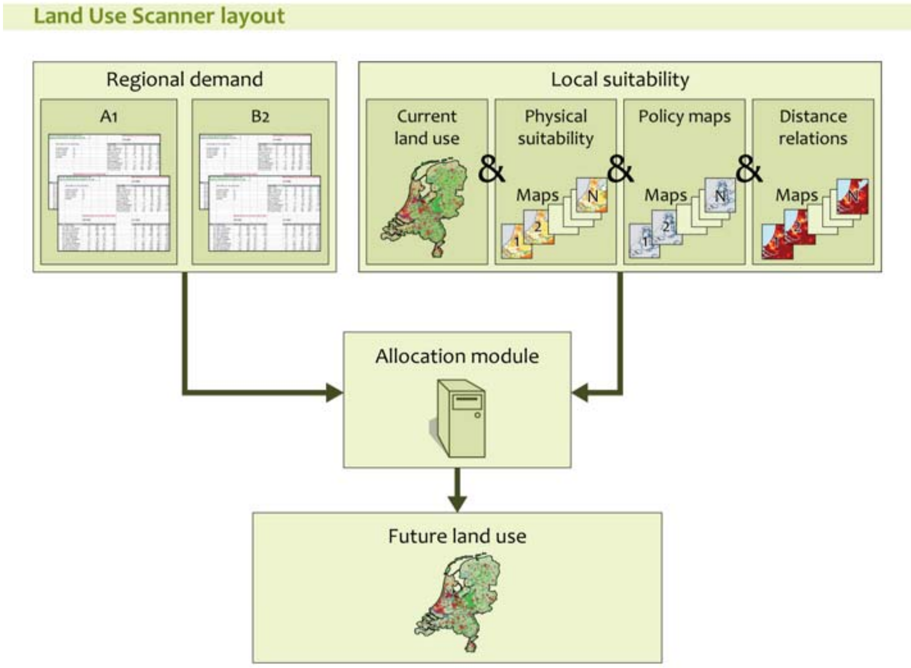

Figure 3 Basic layout of the Land Use Scanner model (source: Koomen et al., 2011a).

External regional projections of the demand for land are used as input for the model. These projections are specific for each land-use type and are derived from, for example, sector-specific models on housing or agriculture provided by specialised institutes or experts (when it comes to functions strongly dependant on policies, such as nature or water management). These projections of demand express for each land-use type the additional land demand. The total of the additional demand and the present area claimed by each land-use function is allocated to individual grid-cells based on the suitability of the cell for that particular land use.

The definition of local suitability uses a large number of geo-datasets that refer to the following aspects: *current land use*, *physical properties*, *operative policies* and *market forces.*

Current land use is the starting point in the simulation of future land use. Various geo-datasets are used to construct a map of current land use in the base year of the simulation. Current land use is an important ingredient in the specification of both total regional demand for land and local suitability. For example, new housing is often located near to existing housing areas. However, because Land Use Scanner also allocates existing land use, current land-use patterns are not necessarily preserved in simulations. Transition costs can play an important role here, too, by preserving existing land use when that use is economically sound.

The advantage of this flexibility is that dynamics in current land use can also be simulated, such as the conversion of obsolete business parks to new housing areas or the demolition of housing in regions with a shrinking population. This flexibility needs to be balanced with the geographical inertia that characterises especially the capital-intensive types of land use (e.g. urban land, greenhouses) and calls for sound information on the aspects that influence transition probability such as demolition costs. To date, this remains a relatively under-explored research area.

The *biophysical properties* of land (e.g. soil type and groundwater level) are especially important for the suitability specification of particular land-use types, such as in agriculture, where they directly influence possible yields, or for nature management, where they determine the possibilities of realising policy aims such as the creation of new wetlands. Biophysical properties are generally considered to be less important for urban functions, since the Netherlands has a long tradition of manipulating its natural conditions, in particular its hydrological conditions.

Operative policies, on the other hand, help steer Dutch land-use developments in many ways, and they are important components in the definition of suitability. The designated zones of the National Ecological Network, where nature will be developed, or the municipal zoning plans are examples of spatial policies that stimulate the allocation of certain types of land use by enhancing its suitability. Conversely, policies can also reduce land suitability, through the definition of restrictions as is exemplified by various zoning laws related to, for example, groundwater protection and the preservation of landscape values.

The *market forces* that steer residential and commercial development, for instance, are generally expressed in distance relations to other, nearby land-use functions. Especially accessibility aspects such as proximity to railway stations, highway exits and airports are considered important factors that influence the location preferences of actors who are active in urban development. Other factors that reflect location preferences are, for example, the levels of service available from urban facilities or the attractiveness of the surrounding landscape.

The selection of the appropriate factors for all land-use types and their relative weighting are crucial steps in the preparation of the allocation of land uses and these largely determine the simulation outcomes. The relative weighting of the factors that describe the biophysical conditions, market forces and operative policies are normally assigned in such a way that they reflect the content of the particular trend, scenario or optimisation that is implemented land-use application.

2.3 Incorporating residential density in land-use allocation

In our approach we combine the strengths of a regional-level land-use and transport interaction model with a local level land-use allocation model. The former model provides the regional projections of numbers of households (and thus residences) while the latter deals with its spatial implications. More specifically we follow the steps listed in Figure 4. These are described in more detail below.

Step 1. Add localised layer information to Land Use Scanner

Step 2. Quantify regional residential land demand

Step 3. Simulate future land-use patterns

Step 4. Update local layer info on residences

Figure 4 Main steps in incorporating residential land-use allocation

1. Add localised layer information to Land Use Scanner

This involves downscaling the current number of actors and objects in 100m grid. <<A description will be added of how this is done and which data sets are used.>>

2. Quantify regional residential land demand

Quantify regional demand for residential land within Land Use Scanner instead of in a separate pre-processing step. Based on a review of existing approaches to obtain residential land demand (e.g. Hoymann, 2010), a formal model will be described that quantifies relationships between residents, residences and land use.

$$D_{r(t1)} = NwRes_{r(t1)} * Ext_r * NwDens_r \qquad \text{(eq.1)}$$

In which:

$D_{r(t1)}$ is the additional demand for residential land in region $_r$ on time step 1 (in hectares);

$NwRes_{r(t1)}$ is the net regional change in housing stock between time step 0 to 1 (absolute numbers);

Ext_r is the share (percentage) of residences that is built outside existing residential areas;

$NwDens_r$ is the average density of urban extensions in region $_r$ (ha/new residence).

The regional increase in number of residences ($NwRes_{r(t1)}$) is based on TigrisXL output. The extensification share (Ext_r) is based on a new analysis. The average density of urban extensions ($NwDens_r$) is based on observed urban expansions (incl. related land use) and scenario-based assumptions. This density includes demand for local facilities (schools, shops, parks), infrastructure (streets, parking lots) and other issues (water storage). This analysis is performed at the regional NUTS3-level that is normally used to define land demand in the model (40 so-called COROP regions). It uses detailed data on the spatial distribution of residents and residences (100 metres resolution) in the past 10 years provided by PBL Netherlands Environmental Assessment Agency. In a subsequent step the observed changes will statistically be linked to characteristics of the regions related to, for example, availability of land, land price, presence of restrictive policies.

3. Simulate future land-use patterns

<< A short description will be added of the model version that is used and its basic specification. >>

4. Update local layer information on residences:

To update the layer info on residences we distinguish between new residential areas (extensions) and density changes within existing residential areas.

Within newly simulated residential areas we apply the following straightforward approach:

$$NrRes_{i(t1)} = 1 / NwDens_r \qquad \text{(eq.2)}$$

In which:

$NrRes_{i(t1}$ is the residential density in grid cell $_i$ (number of residences/ha);

$NwDens_r$ is the average new residential density in region $_r$ described in Eq. 1

Within current residential area we add a change rate on existing, observed densities:

$$NrRes_{i(t1)} = NrRes_{i(t0)} - ChDens_r \qquad \text{(eq.3)}$$

$ChDens_r$ is a region specific density change rate for the period between moment of observation $_{t0}$ and simulation $_{t1}$ (number of residences/hectare).

This change rate can be based on an analysis of regional changes in number of residences in the preceding decade or TigrisXL output:

$$NrRes_{i(t1)} = NrRes_{i\,(t0)} + (1- Ext_r) * NwRes_{r\,(t1)} \qquad \text{(eq.4)}$$

Initially we apply regionally averaged density changes rates to all cells, but in the future we will distinguish between locations. This calls for the specification of a separate allocation routine.

3 Results

As this is work in progress, results are preliminary (if present at all).

3.1 Specifying the residential density module

A spatial analysis was performed of past density changes, focusing on the specification of the following model components:

- Ext_r is the share (percentage) of residences that is built outside existing residential areas;
- $NwDens_r$ is the average density of urban extensions in region $_r$ (ha/new residence).

- $ChDens_r$ is a region specific density change rate for the period between moment of observation $_{t0}$ and simulation $_{t1}$ (number of residences/hectare).

Based on these components, the regional demand for residential land is specified.

<< Figures will be added of base data (residential density difference between 2000 and 2008, land-use difference between 2000-2008) to illustrate level of detail and quality of data.

Table with results and a short textual discussion (a.o. linking observed extensification shares with policy objectives) will be added.

Add table listing number of residences and land demand for two scenarios and/or trend based extrapolation. Preferably add line graph too for Country and/or selected regions. >>

3.2 Simulating future land-use and residential density

<< Figures showing land use 2040 for two scenarios and/or tends based extrapolation will be added. With inset of future residential density. >>

4 Conclusion and discussion

The residential density model allows for more efficient and transparent calculation of residential land demand than previous external procedures. Moreover, input information on numbers of residents and residences and amount of residential land use and related assumptions (e.g. intensification share, residential density) is now accessible within Land Use Scanner, allowing the exploration of scenarios with different urbanisation strategies. Output information will be made available at both the regional and local (100 meter grid cell) level to allow the visualisation of local changes in residential density.

Next steps:

1) Update local layer info on residents

2) Incorporate residential density model in allocation process. This step will make the calculation of residential density a dynamic element in the allocation process instead of a static component whose value is determined before simulation starts. Based on, for example, regional land scarcity (reflected in high shadow prices in the simulation process) residential density and thus its land demand will be able to adapt.

3) Test approach in regional case studies. The applicability of the proposed approach to assess different scenarios of urban development will be tested in regional case studies. These scenarios will combine existing socioeconomic scenarios (provided by PBL) with insights from analyses of driving forces and suggested solution strategies. These new model applications are designed to deal with urban expansion and intensification (case 1) and urban restructuring (case 2).

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