Calibration and validation of the Land Use Scanner allocation algorithms

Netherlands Environmental Assessment Agency

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Abstract

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The Land Use Scanner is a spatial model that simulates future land use. Since its development in 1997, it has been applied in many policy-related land-use projects. In 2005, a completely revised version became available. In this version, land use can be modelled on a reduced scale, the smallest resolution now being 100 metres. Furthermore, the new version offers the possibility to model homogenous or discrete cells (containing only one type of land use) in addition to the heterogeneous or continuous cells (with more types of land use per cell), that were already available in the previous version. Each of these model versions uses its own algorithm to allocate land-use types to individual cells.

In this report, both algorithms are described and their spatial allocation performance is calibrated using multinomial logistic regression, to specify the weights of the factors included in the local cell-based definition of suitability. Furthermore, the two model algorithms were validated by applying the calibrated suitability definition in a subsequent time period. This validation exercise indicates that both model algorithms provide sensible spatial patterns. In fact, the two different modelling approaches produce very comparable results, given equal starting points. In general, we conclude that the model is well-suited to simulate possible future spatial patterns in the scenario or policy-optimisation studies that are typically carried out by the Netherlands Environmental Assessment Agency. The current focus on the spatial allocation behaviour of the model implies that additional modelling aspects relating to the complete modelling chain in which the Land Use Scanner is applied, are not considered. These and other more conceptual modelling issues are covered in the model improvement project that the Netherlands Environmental Assessment Agency started in 2008.

Keywords: land-use modelling, calibration, validation, multinomial logistic regression, spatial optimisation

Contents

Summary

The present report describes the calibration and validation of the spatial allocation performance of the renewed Land Use Scanner. The new version offers a range of resolutions and different allocation algorithms at which simulation is possible. The focus will be on the most detailed resolution (100 metres) and the new allocation algorithm that uses a discrete specification of land use per grid cell. This new approach describes only one type of land use per cell, as opposed to the fractional (probability) description of all possible land-use types in the original, continuous version of the model.

The main objectives of the present analysis are: 1) to assess the potential of the new fine resolution in producing sensible land-use patterns, and 2) to compare the performance of the two available algorithms. Furthermore, the most important location factors in the suitability map definition are pin-pointed. For this analysis, a simplified model configuration is used, that uses nine major types of land use. Starting point for the calibration is the 1993 land use. With multinomial logistic regression analysis, different sets of statistical relations are established, that describe the land-use configuration in 1993. These relations are subsequently used to simulate the land use in 2000. A pixel-by-pixel comparison of the actual, observed land use in 2000 to the simulated land use, indicates the performance of the model.

The initial calibration exercise, which uses the current (1993) land use as an indication of land-use suitability, proves that the model is able to exactly reproduce existing land-use patterns. This shows that the allocation procedure is working correctly; for each land-use type the proper amounts and locations are used. In this respect, it is interesting to note that simulation starts with an empty map. The simulation reproduces current land use by properly describing suitable locations, not through fixing land uses at their present location, as other models do. This has the important advantage of making the model extremely flexible in producing simulations of future land use. This characteristic makes the model very suited to simulate the land-use patterns that may result from specified scenario conditions or policy objectives.

The validation results relating to the statistically derived suitability maps show that the model performs relatively well in simulating agricultural land use and nature. For the more urban categories (recreation, residential and commercial land use) the model performs less well. This may partly be due to limitations of the available data sets and the applied statistical analysis. Inclusion of more detailed and more specific explanatory variables (related to, for example, spatial planning and accessibility) and a focus on the explanation of recent land-use changes may help to improve the performance of the model in this respect.

On a more fundamental level, however, it is clear that socio-economic developments will always have a large degree of uncertainty. Not even the most rigorous calibration offers any guarantee for producing the 'right' simulations of future land use. To cope with this large degree of uncertainty, most socio-economic outlooks on the future apply the scenario method. This implies that the model neither has to replicate past developments, nor has to produce the most probable land-use pattern. It should, first and foremost, be able to produce possible spatial patterns that match the anticipated future conditions set out in scenarios or spatial policy objectives. And, as was discussed above, the model is indeed well-suited to do just that. Furthermore, this means that the outcomes of the model should not be interpreted as fixed predictions for particular locations, but rather as probable spatial patterns.

The validation, furthermore, shows that the two allocation mechanisms, given equal starting points, provide very similar land-use patterns. The new discrete allocation method proved to be very powerful in solving the very large optimisation problem at hand. The applied algorithm finds an exact solution with a desktop PC within several minutes, provided that a feasible solution exists. This calculation time is comparable to the original continuous model. This is an impressive result, as we do not know comparable complex optimisation models that are able to provide such fast results.

The current calibration and validation study focuses on the ability of the model to provide sensible spatial patterns and does not consider additional modelling aspects that influence the simulation results. These relate, first and foremost, to the amount of land-use change that is used in simulations and, more generally, to the complete modelling chain in which the Land Use Scanner is applied. The importance of these issues is briefly discussed in the last section of this report. The model improvement project that the Netherlands Environmental Assessment Agency started in 2008, however, pays specific attention to this and other more conceptual modelling issues.

In general, we conclude that the model is able to produce meaningful land-use patterns that match prescribed condi-

tions. This makes the model well-suited to simulate possible future spatial patterns in the scenario or policy-optimisation studies that are typically carried out by the Netherlands Environmental Assessment Agency.
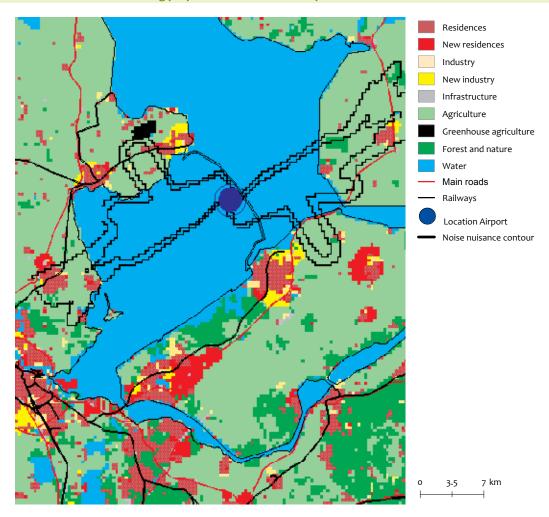
Introduction

The Land Use Scanner is a spatial model that simulates future land use. The model offers an integrated view of all types of land use, dealing with urban, natural and agricultural purposes. Since the development of its first version in 1997, it has been applied in a large number of policy-related research projects. Applications include, among others, the simulation of future land use following different scenarios (Borsboom-van Beurden et al., 2007; Dekkers and Koomen, 2007; Koomen et al., 2008b; Schotten and Heunks, 2001), the evaluation of alternatives for a new national airport (Scholten et al., 1999), the preparation of the Fifth National Physical Planning Report (Schotten et al., 2001b), and an outlook for the prospects of agricultural land use in the Netherlands (Koomen et al., 2005). Apart from these Dutch applications, the model has also been applied in several European countries (Hartje et al., 2005; Hartje et al., 2008; Schotten et al., 2001a; Wagtendonk et al., 2001). A full account of the original model is provided elsewhere (Hilferink and Rietveld, 1999). For an extensive overview of all publications which are related to the Land Use Scanner, the reader is referred to www.lumos.info and www.feweb.vu.nl/gis.

A seriously revised version (4.7) of the model became available in 2005. This new version offers the possibility to use a grid of 100x100 metres, covering the terrestrial Netherlands in about 3.3 million cells. This resolution comes close to the size of actual building blocks and allows for the use of homogenous cells that only describe the dominant land use. The previous version of the model had a 500-metre resolution with heterogeneous cells, each describing the relative proportion of all present land-use types. Together with the introduction of homogenous cells using a dominant land use, a new algorithm has been developed that finds the optimal allocation of land use given the specified demand and suitability definition. This new approach is referred to as the discrete model, as it uses a discrete description of land use per cell: each cell is assigned only one type of land use from the total range of possible land-use types. The original model is in this report referred to as the continuous model, since it uses a continuous description of land use per cell. This approach has previously also been described as probabilistic, to reflect that the outcomes essentially describe the probability that a certain land use will be allocated to a specific purpose. The model has a flexible layout that allows for the selection of five different resolutions, ranging from 100 to 10,000 metres, and the choice of the discrete or continuous model, thus providing a total of 10 basic model types.

To better understand the possibilities and limitations of the new version of the Land Use Scanner, an extensive calibration and validation analysis is performed. The main objectives of this analysis are 1) to assess the potential of the new fine resolution in producing sensible land-use patterns, and 2) to compare the performance of the two available allocation algorithms. The sensibility of the simulated land-use patterns is expressed as the degree to which these correspond to the observed land-use patterns. The relative performance of the individual algorithms can be assessed by comparing the degree to which the respective simulation outcomes correspond to the observed land-use patterns. The calibration exercise also intends to pinpoint some of the most important location factors that have produced the current land-use patterns and reveal their relative weights. As such, the analysis provides useful information for the definition of the suitability maps of the model.

The specific focus on the ability of the model to provide sensible spatial patterns implies that several other validation issues are not considered in this study. These relate, first and foremost, to the amount of land-use change that is used in simulations and, more general, to the complete modelling chain in which the Land Use Scanner is only one of the many instruments that link scenario assumptions to environmental impacts. The specific position of the Land Use Scanner is introduced in the following section, which discusses typical applications in the Dutch planning context. We have chosen for a specific focus on the spatial allocation performance for several reasons. The principle reason is pragmatic; having only limited resources available we preferred to do a thorough validation of one modelling aspect, rather than performing a limited validation of many different aspects. As the main objective of any land-use model is to provide sensible spatial patterns, this aspect is an obvious choice in this first extensive calibration and validation of the model. The validation of other modelling aspects, such as the quantities of land-use change that are used in the simulations, is more complex as it calls for inclusion of the other modelling tools that provide this type of information. However, these and other more conceptual validation issues are currently receiving research attention, as will be discussed in the concluding section.

Simulated land-use changes, following a possible new location of the Dutch national airport: bright red indicates new residential development, bright yellow indicates new commercial development (Van de Velde et al., 1997).
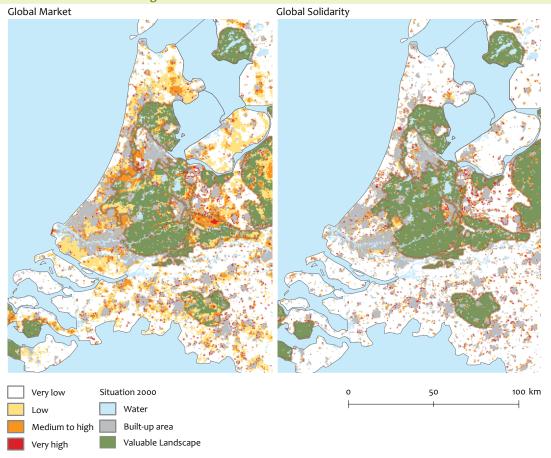
1.1 The Land Use Scanner in the Dutch planning context

The objective of most Dutch planning-related Land Use Scanner applications is to provide probable spatial patterns related to predefined conditions. These conditions are normally related to scenario assumptions or specific policy interventions, as is exemplified by the brief description of two typical applications below. These examples refer to a regional impact study and a national scenario-based application.

An initial regional application of the Land Use Scanner focussed on the possible spatial impact of a new national airport (Scholten et al., 1999; Van de Velde et al., 1997). This analysis was commissioned by a multi-ministerial task force, which examined the possible relocation of the Dutch national airport. The changes in land-use patterns were simulated for nine different location alternatives. These simulations followed a set of assumptions regarding the expected increase in the amount of land used for residential and commercial purposes, and the related locational preferences. The assumptions were founded in a literature review. Figure 1.1 presents an example of a map of simulated dominant land-use for one

of the location alternatives. The recent introduction of a more detailed model version offers a tempting possibility to apply the model in regional case studies. This was, for example, demonstrated at the province level (Borsboom-van Beurden et al., 2007; Bouwman et al., 2006; Koomen et al., 2008a). It also creates the possibility to develop more detailed, three-dimensional representations of the Land Use Scanner outcomes (Borsboom-van Beurden et al., 2006; Lloret et al., 2008).

Most Land Use Scanner applications on the national level follow the popular scenario-based approach to deal with the uncertainties relating to future spatial developments. By describing a set of opposing views on the future — as is common in, for example, the reports of the Intergovernmental Panel on Climate Change (IPCC, 2001) — a broad range of spatial developments can be simulated, offering an overview of possible land-use changes. Each scenario will not necessarily contain the most likely prospects, but, as a whole, the simulations provide the bandwidth of possible land-use changes. In such a study, the individual scenarios should, in fact, not strive to be as probable as possible, but should stir

Global Market   Global Solidarity

☐ Very low	Situation 2000	
☐ Low	☐ Water	
☐ Medium to high	☐ Built-up area	
☐ Very high	☐ Valuable Landscape	

0   50   100 km

Land use simulated according to the A1 (left) and B1 (right) scenarios: the intensity of the red colour indicates a possible increase in urban pressure, the green areas inside the grey contours signify valuable landscapes (Borsboom-van Beurden et al., 2005).

the imagination and broaden the view on the future. Important elements are: plausible unexpectedness and informational vividness (Xiang and Clarke, 2003). An example of such a scenario-based simulation of land-use change is offered by (Borsboom-van Beurden et al., 2007; Borsboom-van Beurden et al., 2005). This analysis was performed to evaluate the possible impact on nature and landscape in scenarios on the future, as described in the first national sustainability outlook (MNP, 2004). The qualitative storylines of the original scenario framework were translated in spatially explicit assumptions, regarding the locational preferences and future demand of a large number of land-use types, by means of expert workshops and sector specific regional models. The results of the study were subsequently used to inform the National Parliament. The general public was also informed through, for example, publicity in the national media (Schreuder, 2005). This study pointed out that increased land use by housing, employment and leisure, will contribute to further urbanisation, especially in the centre of the Netherlands. This will result in deterioration of nature areas and valuable landscapes, depending upon the degree of government protection assumed in a scenario (Figure 1.2). Another recent application at the national level simulated future land-use patterns according to two trend-based scenarios and

subsequently optimised the projected spatial developments according to specific planning objectives to show possible alternative land-use configurations that may result from policy interventions (MNP, 2007).

The above mentioned applications have in common that they follow a *what-if* approach; they indicate *what* may happen *if* certain conditions occur. This implies that the main task of the applied land-use model is not so much to create the most probable, future land-use pattern, but rather to produce outcomes that match the envisioned future conditions.

1.2 Report layout

The present report is organised as follows. The following section will further introduce the Land Use Scanner. Here, the model basics and its two available allocation algorithms are briefly discussed, and previous calibration efforts are mentioned. Section 3 proceeds to present the methodology applied in this report. The Sections 4 and 5 then describe the actual calibration and validation of the Land Use Scanner. The final section lists the plans for further research.
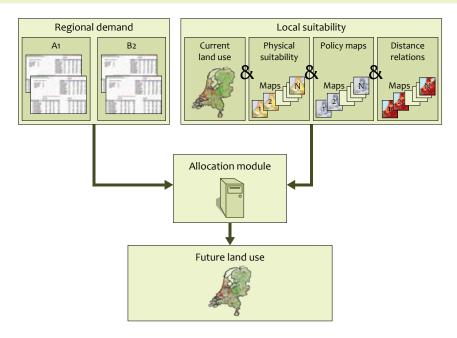
Land Use Scanner

2

The Land Use Scanner is a GIS-based model that produces simulations of future land use, based on the integration of sector-specific inputs from dedicated models. The model is based on demand-supply interaction for land, with sectors competing for allocation within suitability and policy constraints. It uses a comparatively static approach that simulates a future state, in a limited number of time steps. Recent applications simulate land-use patterns in three subsequent time steps (MNP, 2007), whereas initial applications used only one or two. Unlike many other land-use models, the objective of the Land Use Scanner is not to forecast the dimension of land-use change, but rather to integrate and allocate future land-use demand from different sector-specific models or experts. This is depicted in Figure 2.1, presenting the basic structure of the Land Use Scanner.

External regional projections of land-use change, which are usually referred to as demands or claims, are used as input for the model. These are land-use type specific and can be derived from, for example, sector-specific models of specialised institutes. The predicted land-use changes are considered as an additional demand for the different land-use types, compared with the present area in use, for each land-use type. The total of the additional demand and the present area for each type of land use is allocated to individual grid-cells, based on the suitability of the cell. This definition of local suitability may incorporate a large number of spatial data sets, referring to the following aspects that are discussed below: *current land use*, *physical properties*, *operative policies* and *market forces,* generally expressed in distances related to nearby land uses.

Current land use offers the starting point in the simulation of future land use. Therefore, it is an important ingredient in the specification of both the regional demand and the local suitability. Current land-use patterns are, however, not necessarily preserved in model simulations. This offers the advantage of having a large degree of freedom in generating future simulations, according to scenario specifications, but calls for attention when current land-use patterns are likely to be preserved.

Figure 2.1

Basic layout of the Land Use Scanner.

The *physical properties* of the land (e.g. soil type and ground-water level) are especially important for the suitability specification of agricultural land-use types as they directly influence possible yields. They are generally considered to be less important to urban purposes, as the Netherlands have a long tradition of manipulating their natural conditions.

However, *operative policies* help steer Dutch land-use developments in many ways, and are important components in the definition of suitability. The national nature development zones and the municipal urbanisation plans are examples of spatial policies that stimulate the allocation of certain types of land use. Restrictions are offered by various zoning laws related to, for example, water management and the preservation of landscape values.

The *market forces* that steer residential and commercial development, for instance, are generally expressed in distance relations. Especially the proximity to railway stations, highway exits and airports, are considered important factors that reflect the locational preferences of the actors, which are active in urban development. Other factors that reflect such preferences are, for example, the number of urban facilities or the attractiveness of the surrounding landscape.

The selection of the appropriate factors for each of these components and their relative weighing, are crucial steps in the definition of the suitability maps and largely determine the simulation outcomes. The relative weights of the factors, which describe the market forces and operative policies, are normally assigned in such a way that they reflect the scenario storylines. Obviously, these scenario-related suitability definitions cannot be validated, as they essentially reflect the imagination of the modeller. Instead, the current calibration effort is mainly aimed at assessing the performance of the available allocation algorithms. An additional objective, however, is to help pinpoint the most important location factors in the suitability map definition. Furthermore, the relative weighing of the suitability values of the different land-use types will be evaluated, as a recurring issue in their definition is how to scale the values of, for instance, residential land use in relation to agriculture.

The following sections describe the two allocation algorithms in more detail. The last section briefly discusses previous calibration attempts for the Land Use Scanner and summarises several studies which have tried to quantify the importance of various location factors for past land-use changes.

2.1 Continuous model

The original, continuous model employs a logit-type approach, derived from discrete choice theory. Nobel prize winner McFadden has made important contributions to this approach of modelling choices between mutually exclusive alternatives (McFadden, 1978). In this theory, the probability that an individual selects a certain alternative is dependent on the utility of that specific alternative, in relation to the total utility of all alternatives. This probability is, given its definition, expressed as a value between 0 and 1, but it will never

reach these extremes. When translated into land use, this approach explains the probability of a certain type of land use at a certain location, based on the utility of that location for that specific type of use, in relation to the total utility of all possible uses. The utility of a location can be interpreted as its suitability for a certain use. This suitability is a combination of positive and negative factors that approximate benefits and costs. The higher the utility (suitability) for a land-use type, the higher the probability that the cell will be used for that type. Suitability is assessed by potential users and can also be interpreted as a bid price. After all, the user deriving the highest benefit from a location will offer the highest price. Furthermore, the model is constrained by two conditions, namely, the overall demand for each type of land use, and the amount of land which is available. By imposing these conditions, a doubly constrained logit model is established, in which the expected amount of land in cell c that will be used for land-use type j is essentially formulated as:

$$M_{cj} = a_j * b_c * e^{S_{cj}} \qquad (1)$$

in which:

M_{cj} is the amount of land in cell *c* expected to be used for land-use type *j;*

a_j is the demand balancing factor (condition 1) that ensures that the total amount of allocated land for land-use type *j* equals the sector-specific claim;

b_c is the supply balancing factor (condition 2) that makes sure the total amount of allocated land in cell *c* does not exceed the amount of land that is available for that particular cell;

S_{cj} is the suitability of cell *c* for land-use type *j,* based on its physical properties, operative policies and neighbourhood relations. The importance of the suitability value can be set by adjusting a scaling parameter.

The appropriate a_j values that meet the demand of all land-use types, are found in an iterative process, as is also discussed by (Dekkers and Koomen, 2007). This iterative approach, in fact, simulates a bidding process between competing land users (or, more precisely, land-use classes). Each use will try to get its total demand satisfied, but may be outbid by another category that derives higher benefits from the land. Thus, it can be said that the model, in a simplified way, mimics the land market. The government policies that strongly limit the free functioning of the Dutch land market, can be included in this process in the suitability map definition by means of taxes and subsidies. In fact, the simulation process produces a kind of shadow price for land within the cells. This is discussed in more detail elsewhere (Koomen and Buurman, 2002).

In reality, the allocation process is more complex than suggested in the described basic formulation. The most important extensions are briefly discussed below:
- The location of a selected number of land-use types (infrastructure, water, exterior) is fixed in the model

and anticipated developments (e.g. the construction of a new railroad) are supplied exogenously to the simulations;

– The land-use claims are specified per region and this regional division may differ per land-use type, thus creating a complex set of demand constraints;

– Minimum and maximum claims are introduced to make sure that the model has a feasible solution. For land-use types with a minimum claim it is possible to allocate more land. With a maximum claim it is possible to allocate less land. The latter type of claim is essential when the total of all land-use claims exceeds the available amount of land;

– To reflect the fact that urban land users, in general, will outbid other users at locations that are equally well suited for either type of land use, a monetary scaling of the suitability maps has recently been introduced (Borsboom-van Beurden et al., 2005; Groen et al., 2004). In this approach, the maximum suitability value per land-use type is related to a realistic land price, ranging from, for example, 2.5 €/m² for nature areas to 35 €/m² for residential areas. The merits of this approach are currently under study by others (Dekkers, 2005).

A more extensive mathematical description of the model and its extensions is provided in a previous paper (Hilferink and Rietveld, 1999).

The continuous model directly translates the probability that a cell will be used for a certain land-use type on a certain amount of land. Thus, a probability of 0.9, in the case of a 100-metre grid, will result in 0.9 ha. This straightforward approach is easy to implement and interpret, but has the disadvantage of potentially providing very small surface areas for many different land-use types in a cell. This will occur, especially, when the suitability maps have little spatial differentiation. A possible solution for this issue is the inclusion of a threshold value in the translation of probabilities in surface areas. Allocation can then be limited to those land-use types that, for example, have a probability of 0.2 or higher. The inclusion of such a threshold value calls for an adjustment of the allocation algorithm, to make sure that all land-use claims are met. This is feasible, nevertheless, and has been applied in the *Natuurplangenerator* (Eupen and Nieuwenhuizen, 2002), which — in many ways — is similar to the Land Use Scanner. The experience with this minimal probability teaches that insignificant quantities of land use will be set to zero and, if this threshold value is raised, the model will have difficulty finding an optimum. This is caused by the possibility that all probabilities are below the threshold value. Because of these disadvantages it is not recommended to raise the threshold value.

For visualisation purposes the simulation outcomes are normally aggregated and simplified in such a way, that each cell portrays the single dominant category from a number of major categories. This simplification has, however, substantial influence on the apparent results and may lead to a serious over-representation of some categories and an under-representation of others. To prevent the above mentioned issues related to the translation and visualisation of the probability related outcomes, an allocation algorithm was introduced that deals with homogenous cells, as is discussed below.

2.2 Discrete model

The discrete allocation model allocates equal units of land (cells) to those land-use types that have the highest suitability, taking into account the regional land-use demand. This discrete allocation problem is solved through a form of linear programming. The solution of which is considered optimal when the sum of all suitability values corresponding to the allocated land use is maximal.

This allocation is subject to the following constraints:
– the amount of land allocated to a cell cannot be negative;
– in total only 1 hectare can be allocated to a cell;
– the total amount of land allocated to a specific land-use type in a region should be between the minimum and maximum claim for that region.

Mathematically, we can formulate the allocation problem as:

$$\max_X \sum_{cj} S_{cj} X_{cj} \qquad (2)$$

subject to:

$$X_{cj} \geq 0 \quad \text{for each } c \text{ and } j;$$

$$\sum_j X_{cj} = 1 \quad \text{for each } c;$$

$$L_{jr} \leq \sum X_{cj} \leq H_{jr} \quad \text{for each } j \text{ and } r \text{ for which claims are specified;}$$

in which:

X_{cj} is the amount of land allocated to cell c to be used for land-use type j;

S_{cj} is the suitability of cell c for land-use type j;

L_{jr} is the minimum claim for land-use type j in region r; and

H_{jr} is the maximum claim for land-use type j in region r.

The regions for which the claims are specified may partially overlap, but for each land-use type j, a grid cell c can only be related to one pair of minimum and maximum claims. Since all of these constraints relate Xcj to one minimum claim, one maximum claim (which cannot both be binding) and one grid cell with a capacity of 1 hectare, it follows that if all minimum and maximum claims are integers and feasible solutions exist, the set of optimal solutions is not empty and cornered by basic solutions in which each Xcj is either 0 or 1 hectare.

The problem at hand is comparable to the well-known Hitchcock transportation problem that is common in transport–cost minimisation and, more specifically, the semi-assignment problem (Schrijver, 2003; Volgenant, 1996). The

objective here is to find the optimal distribution, in terms of minimised distribution costs of units of different homogenous goods, from a set of origins to a set of destinations under the constraints of a limited supply of goods, a fixed demand, and fixed transportation costs per unit for each origin–destination pair. The semi-assignment problem has the additional characteristic that all origin capacities are integer and the demand of each destination is one unit. Both are special cases of linear programming problems. The discrete allocation algorithm has two additional characteristics, which are not incorporated in the classical semi-assignment problem formulation: (1) we can specify several, (partially) overlapping regions for the claims (although the regions of claims for the same land-use type must be disjoint); and (2) it is possible to apply distinct minimum and maximum claims.

Our problem, with its very large number of variables, calls for a specific, efficient algorithm. To improve the efficiency, we apply a scaling procedure and also use a threshold value. Scaling means that we use growing samples of cells in an iterative optimisation process that has proven to be fast (Tokuyama and Nakano, 1995). For each sample an optimisation is performed. After each optimisation, the sample is enlarged and the shadow prices in the optimisation process are updated in such way that the (downscaled) regional constraints remain respected. To limit the number of alternatives under consideration we use a threshold value: only allocation choices that are potentially optimal are placed in the priority queues for each competing claim. An important advantage of the applied algorithm is that we are able to find an exact solution using a desktop PC (Pentium IV-2.8 GHz, 1 GB internal memory), within several minutes, provided that feasible solutions exist and all suitability maps have been prepared in an initial model run. Running the model for the first time takes just over an hour, as all base data layers have to be constructed. These data sets are then stored in the application files (in a temporary folder) to speed up further calculations.

The constraints that are applied in the new discrete allocation model are equal to the demand and supply balancing factors applied in the original, continuous version of the model. In fact, all the extensions to the original model related to the fixed location of certain land-use types, the use of regional claims, the incorporation of minimum/maximum claims and the monetary scaling of the suitability maps, also apply to the discrete model. Similar to the original model, the applied optimisation algorithm aims to find shadow prices for the regional demand constraints that increase or decrease the suitability values, such that the allocation based on the adjusted suitability values corresponds to the regional claims. The main difference of the discrete model is that each cell only has one land-use type allocated, meaning that for each land-use type the share of occupation is zero or one. However, from a theoretical perspective the models are equivalent when the scaling parameter that defines the importance of the suitability values would become infinitely large. In the latter case, the continuous model would also strictly follow the suitability definition in the allocation and produce homogenous cells. This procedure, however, is theoretical and cannot be applied in the calculations due to computational limitations.

2.3 Previous calibration efforts

Many different model components of the original, continuous land-use model, have received ample research attention over the past 10 years. Initial calibration efforts focused on the appropriate number of iterations and estimation of the β-parameter (Hilferink and Rietveld, 1999). Subsequent efforts analysed the development of the shadow prices and concluded that the model neatly converged to equilibrium prices, when the minimum and maximum claims were used in such a way that a feasible solution existed (Ransijn et al., 2001).

A first attempt to calibrate the suitability maps for individual land-use types, was done for single and multi-family dwellings (Rietveld and Wagtendonk, 2004; Wagtendonk and Rietveld, 2000). The main factors influencing the location of new residential areas were analysed, in the period from 1980 to 1995, by means of binomial logistic regression. They claim the most significant variables to be: 'the proximity of a location to existing residential areas; location in new towns, receiving government support; the accessibility of workplaces; distance to railway stations; and, to a lesser extent, the accessibility of nature, surface water, and recreational areas'. These findings have been applied in a simulation of new residential development in the 1995 to 2020 period (Schotten et al., 2001b).

A further attempt at calibrating the suitability maps in the Land Use Scanner, was focussed on commercial land use (Wagtendonk and Schotten, 2000). The analysis of the location factors, which contributed to the growth of commercial areas (trade, industry and services) in the 1981 to 1993 period, proved the importance of whether a location was situated in the city centre or at the outskirts, and also quantified the impact of the distance to railway stations and highway exits. These results were used in Land Use Scanner simulations of commercial land use in 1993, and were visually compared to the actual commercial land use in that year. This comparison proved the potential of this approach, but also indicated two important drawbacks: (1) regional differences in suitability for specific land uses could not directly be accounted for and (2) historic concentrations, pre-dating the 1981 to 1993 development, were not explained very well, with this approach. These issues are solved in subsequent Land Use Scanner simulations through the inclusion of regionally defined land-use claims, which take into account the differences in commercial development per region, and the explicit inclusion of current land use in the description of suitability.

The wealth of general research dedicated to the location factors that influence land-use development, also provides valuable information for the calibration of the Land Use Scanner. Especially relevant in the Dutch context, is the work of (Verburg et al., 2004) where binomial logistic regression was applied to assess 'the probability of land-use change at a certain location, relative to all other options'. This approach was selected instead of multinomial logistic regression, to be able to use different explanatory factors for the different types of land-use change. The analysis made use of a 500-metre grid, which described a single, dominant land use per cell. This aggregation was based on the majority rule, but a

correction was applied to ensure that the total area for each land use corresponded to the underlying higher resolution base maps. The analysis explained the observed 1989 land use, from a series of location characteristics that were considered relevant for the historic development of the Dutch landscape. These characteristics consisted of the biogeophysical conditions (soil type and altitude), the distance to open water (coast and main rivers) and the distance to historic town centres. This set of explanatory variables worked well to explain the location of agriculture and nature. Urban development could not be easily explained, possibly indicating the importance of non-spatial self-organising processes, and the difficulty to represent the temporal dynamics of land-use change in a static analysis. The latter part of the analysis, therefore, focused on the major short-term land-use changes observed in the 1989 to 1996 period, being the development of new residential, industrial/commercial and recreation areas. These changes were no longer related to biophysical properties, but rather to spatial policies, accessibility and neighbourhood interactions. The most important location factors, which were distinguished in the study of Verburg and others, are normally also included in the suitability maps of the Land Use Scanner.

A major disadvantage of the studies described above, is that they tend to focus on the probability of occurrence of single land-use types. None of the studies examine this probability in relation to the probability of occurrence of the other land-use types, as is the topic of the present study.

An initial integrated validation of the Land Use Scanner was performed as part of an extensive comparison of several contemporary land-use change models (Pontius Jr. et al., 2008). The validation followed a straightforward, quantitative approach, in which a map with observed land use of the initial year is compared to maps with observed and predicted land use of a subsequent year. This set of maps allows for the comparison between actual change and predicted change and, furthermore, assesses the performance of the model in relation to a null model of persistence. The latter indicates whether the model performs better than a no-change approach. These comparisons are performed at multiple resolutions, to analyse whether the observed inaccuracy can be attributed to relatively small locational errors. For the Land Use Scanner this analysis was performed on an adjusted scenario-based simulation of the year 2000, based on 1996 maps, without a preceding calibration effort. The amount of land-use change per land-use type (claims) was derived from a 1981 to 1996 trend analysis. First and foremost, the exercise showed the strong impact of the reformatting of the original, heterogeneous output maps, to the homogenous, maps of dominant land-use needed for the validation. The inaccuracy introduced by the reformatting turned out to be larger than the actual change in the short observation period. Other issues that hamper this validation, are the inconsistencies in the base maps of observed land use, obscuring the actual land-use changes. The reformatting issue does not apply to the present validation analysis, because a different method is presented for comparing the simulation results of the continuous model (see the discussion on map comparison in Section 3). The issue is absent in the presented analysis of the discrete model, because discrete maps of both current and simulated land use are being used. In the actual land-use simulations, however, a similar issue may occur when the discrete simulation starts from a base map that uses a heterogeneous, continuous description of land use per cell. Therefore, we recommend that upcoming simulations start from a data set which uses a discrete specification of current land use.

Methodology 3

To assess the potential of the new fine resolution in producing sensible land-use patterns and to compare the performance of the two available algorithms, a two-step approach is used that first calibrates the model and then validates the simulation results for a subsequent time step, for which a reference data set with observed land use is available. This strict distinction between the calibration and validation phase means that only information available at the initial calibration time step is used to tune the model. This is advocated in literature (Pontius Jr. et al., 2004) and means that we are able to properly assess the predictive power of the model. In the calibration step the model's suitability maps are tuned, based on a statistical analysis of the observed land-use patterns of 1993. The obtained relations are then used to simulate land use in 2000. A pixel-by-pixel comparison between the simulated and the observed land use of 1993 and 2000, reveals the performance of the model. This section describes the most important elements in the applied methodology: the incorporated land-use data sets, the statistical regression analysis and the applied map comparison methods.

The analysis is performed on the two available 100-metre models. This choice is motivated by our special interest in assessing the potential of the new fine resolution, and comparing the performance of the two available allocation algorithms. For computational reasons we use a simplified model configuration that simulates five major types of land use and uses only one time step in the simulation process. For the calibration and validation we use the exact amounts of land per type for 1993 and 2000, respectively. The analysis, thus, focuses solely on the simulated land-use patterns and not on the amount of land-use change. This distinction is common in map comparison research (e.g. Pontius Jr., 2000) and, in our case, means that we only assess the functioning of the allocation algorithms and the impact of the suitability definitions and not of the procedures that are normally used for obtaining future land-use demand. As the latter information is normally derived from external sources, we do not consider this a major drawback in the scope of the current calibration and validation analysis (for additional validation aspects, see Chapter 6).

3.1 Land-use data

Starting point in this calibration effort is the 1993 land use, based on the spatial land-use data set of the Central Bureau

for Statistics (CBS, 1997). This data set, with 34 classes, has been reclassified in nine major types of land use: agriculture, nature, commercial areas, residential areas, recreation, infrastructure, other, water, exterior. The first five land-use types are simulated by the model. The remaining land-use types have a pre-defined location, which is not influenced by model-simulation. This limited set of land-use types has several advantages; it provides a clear insight in the allocation process, it is relevant in policy evaluation studies, and it allows the use of a standard package for subsequent statistical analyses.

To apply the original 25-metre grid land-use data set in the Land Use Scanner that uses a 100-metre resolution, the data were also aggregated to this coarser resolution by using the majority rule. This aggregation leads to an over representation of the land-use types that structurally claim most (agricultural and residential land), but not all of the constituting grid cells. Under-representation of certain land-use types occurs when these, in general cover only a small part of the aggregated cells. Table 3.1 shows that especially the impact of under-representation is considerable for infrastructure and the remaining land-use type 'other'. This does not pose a major problem to our simulations as the location of these land-use types are supplied exogenously to the model. The aggregation impact for the land-use types that are actually simulated in the model is considered to be of minor importance as their total area in the 100-metre grid does not differ more than 4% from the original 25-metre grid.

A major disadvantage of the available land-use data sets is that they are not methodologically consistent through time. A number of unlikely conversions become apparent, when a pixel-by-pixel transition matrix is created. Table 2 summarises the results of this analysis. The conversion of about 13,000 ha of residential areas and 10,000 ha of infrastructure into agriculture, for example, is highly unlikely in the Netherlands, which are characterised by a continuously increasing degree of urbanisation. These conversions are related to changes in the data collection and classification methods (CBS, 1997; CBS, 2002; Raziei and Evers, 2001). Through the changed methodology, unpaved and partially paved roads, the shoulders of paved roads and railroads, for example, have been reclassified according to the surrounding land uses (mainly agriculture and nature). The observed conversion of residential land into agricultural land mainly refers to sparsely built-up areas, in elongated rural villages and other hamlets

Table 3.1

Total area covered by main land-use types in 1993 for the 25-metre base grid and the aggregated 100-metre grid

	Area 25m grid [ha]	Area 100m grid [ha]	Difference [ha]	Difference [%]
Agriculture	2,393,342	2,490,662	97,320	4.1%
Nature	456,644	453,070	-3,574	-0.8%
Residential	273,499	283,741	10,242	3.7%
Commercial	101,926	102,039	113	0.1%
Recreation	30,707	30,490	-217	-0.7%
Infrastructure	109,224	38,937	-70,287	-64.4%
Other	25,860	14,071	-11,789	-45.6%
Water	761,797	740,367	-21,430	-2.8%
Exterior	4,622,000	4,621,623	-377	0.0%

Matrix of transitions in observed dominant land use at a 100-metre resolution   Table 3.2

2000 \ 1993	Agriculture	Nature	Residential	Commercial	Recreation	Infra.	Other	Water	Exterior	Total 2000
Agriculture	2425550	7751	12968	2759	976	10232	2344	2223	132	2464935
Nature	23606	435958	2441	2599	3212	2524	778	1543	38	472699
Residential	24597	3660	258971	12221	835	2667	6320	725	8	310004
Commercial	6003	879	6768	76782	164	1127	244	444	5	92416
Recreation	2112	1094	448	488	23503	167	96	282	4	28194
Infra.	2952	719	864	1064	82	21475	251	239	0	27646
Other	2108	294	336	2495	49	205	3726	274	3	9490
Water	3638	2700	918	3628	1668	538	311	734629	291027	1039057
Exterior	96	15	27	3	1	2	1	8	4330406	4330559
Total 1993	2490662	453070	283741	102039	30490	38937	14071	740367	4621623	8775000

Note: the figures denote hectares, the retention frequencies are shaded grey.

that are considered not to be fully built-up anymore, in the new classification method.
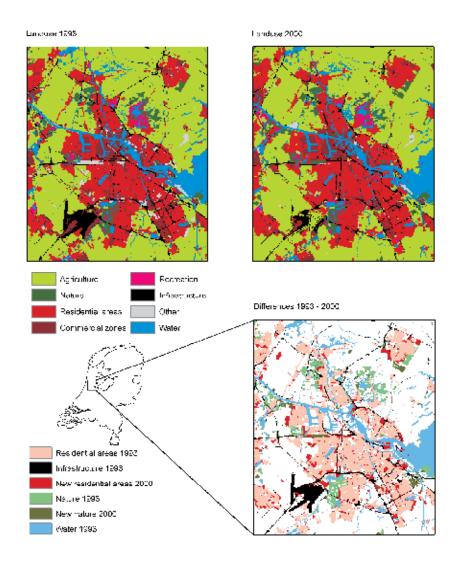
In fact, many of the changes in Table 3.2 have to be viewed with caution. This is especially true for the loss of infrastructure, as was discussed above, the loss of water and the local increase in agricultural areas. Discarding the changes in the exterior that were partly introduced in the subsequent data treatment process, these suspicious changes apply to over 60,000 hectares. This is equivalent to almost 36% of all observed changes other than those in the exterior. Not all of these observed changes are necessarily erroneous, but many of them are likely to be related to phenomena, such as: changes in the classification methodology; changes in the perception of the data collector (for example, when agricultural areas also have natural or recreational values), differences in the water levels at the time of observation (that may account for local gain or loss of water filled areas) or locational mismatches between the different data sets (that may suggest wandering land-use objects). It is evident, that such methodological inconsistencies strongly hamper the analysis of actual changes. The inconsistencies also present a major difficulty in assessing the performance of a land-use simulation, as it is difficult to distinguish between actual and apparent changes.

Figure 3.1 shows the land-use data sets and their major differences, for an area around Amsterdam. The difference map presents the two most common conversions: the conversion of agricultural land into residential areas and into nature. It is clear that most transitions occur in large, contiguous areas, which are normally adjacent to existing residential or natural areas. A comparison of the land use in 1993 and 2000 also

indicates where infrastructure has disappeared, since 1993. This is mainly the case for secondary roads, which are represented as smaller areas leading to an increase in the adjacent, agricultural land use in 2000. The large infrastructural complex (Schiphol airport) is also represented by a smaller area in 2000, again leading to an increase in agriculture. These unwanted conversions are corrected, by excluding the 1993 infrastructural locations from the calibration and validation. In fact, all locations with an exogenous land-use type, in either 1993 or 2000, are excluded in the subsequent calibration and validation exercises.

3.2 Regression analysis

Different sets of statistical relations that describe the land-use configuration in 1993 are established by using multinomial logistic regression (MNL) analysis. This method of regression is useful in situations where categories in a dependent variable, based on values of a set of independent variables, have to be predicted. The method is similar to binomial logistic regression, but the dependent variable is not restricted to two categories. The main advantage of MNL regression is the possibility of estimating the relative probabilities for each category in the dependent variable, with a set of interrelated logistic equations. This is an advantage compared to the alternative approach of using a set of separate binomial logistic regressions that would not estimate these probabilities relative to each other. The dependent variable has to be categorical and, in this case, it relates to the five types of land use that are used in the simulation. Agriculture is used as a reference category in the analysis, meaning that all probabili-

Comparison of the observed 1993 and 2000 land use.

ties are estimated relative to this category. The independent variables in the analysis can be factors or co-variants and, in our case, relate to the surrounding land use, the proximity of infrastructure and specific policy maps.

Applied to the statistical analysis of land-use patterns, the selected approach explains the probability of a certain type of land use at a certain location, based on the utility of that location for that specific type of use, in relation to the total utility of all possible uses. The utility of a location can be interpreted as its suitability for a certain use, and is described with several geographical data sets, which represent location factors. This can be formulated as follows:

$$P_{cj} = e^{\beta * X_{cj}} \Big/ \sum_{k} e^{\beta * X_{ck}} \qquad (3)$$

Where:

P_{cj} is the probability for cell *c* being used for land-use type *j*;

e   is the basis for the natural logarithm;

ß   is a vector of estimation parameters for all variables *x*;

X_{cj} is a set of location factors (explanatory variables) for cell *c* for land-use type *j*; and

X_{ck} is a set of location factors for cell *c* for all (*k*) land-use types.

This logit specification is identical to the original, continuous allocation model and, thus, allows for a straightforward inclusion of the estimated coefficients in the suitability maps of the Land Use Scanner. The suitability value of the reference category is 0 in all locations, but since the other suitabilities are estimated relative to this value, it is still possible to also

Independent variable	Explanation
Railways1_1	Buffer of 100 metres around the railways (derived from the original land-use file from Statistics Netherlands, CBS, 1997)
Train_station_8	distance to nearest train station indicated as an index value between 1 and 8 (derived from: AVV, 1994)
Main_road1_1	Buffer of 100 metres around main roads (derived from the original land-use file from the Statistics Netherlands, CBS, 1997)
EMS1990	Ecological Main Structure, Designated areas for nature areas of high quality (RIVM et al., 1997)
Natura 2000	European network of protected nature areas (IKC-Natuurbeheer, 1993)

simulate agricultural land use with the model. In fact, using another reference category would yield different coefficients but produce an identical land-use map after simulation.

3.2.1 Selection of independent variables

Most of the selected independent variables in the multinomial logistic regression analysis are related to the surrounding land-use types, as these are known to greatly influence land use at a certain location (Verburg et al., 2004). A total of 27 variables were initially distinguished to describe the land use in three sets of rings surrounding any given cell. These rings contain the 8 immediately neighbouring cells (ring 1), the following 40 cells (rings 2-3), and the subsequent 312 cells (rings 4-9), see Figure 3.2. For each of these three sets of rings, the total number of cells that belong to each of the nine distinguished land-use types is expressed as an integer value, ranging from 0 to 8. For ring 1 this integer corresponds exactly with the observed number of cells; for the combination of rings 2 and 3, this integer is the rounded value of the total number of cells dived by 5 and 39, respectively. This so-called autologistic specification estimates the probability that a certain land use occurs, as a function of the total number of cells that belong to each of the nine distinguished land-use types. Implementation of the suitability values that are, thus, derived causes the model to perform in a neighbourhood-oriented manner that is similar to classical Cellular Automata.

In addition to the above autologistic specification, a number of location characteristics were also added. These extra independent variables relate to two types of driving forces that are considered important in land-use development: accessibility (distance to stations and presence of railways and main roads) and spatial policies (related to nature development and nature preservation policies). Table 3.3 presents a short overview of the additional variables. The impact of other spatial variables related to the presence of, for example, underground infrastructure, power lines, soil subsidence, motorway exits, airport noise contours and the borders of the *Green Heart* (the central open space surrounded by the rim of major Dutch cities known as the *Randstad*), was tested in initial model specifications, but did not yield statistically significant results. Inclusion of a more extensive set of variables is, however, considered for future research.

3.2.2 Estimation results

The statistical analysis was performed with the standard software package SPSS (version 13) using 19 different explanatory variables, 14 of which describe the presence of a land-use type in one of the three sets of rings surrounding the cell. The remaining five variables refer to accessibility and spatial poli-

cies. The coefficients resulting from the regression analysis are presented in Table 3.4. The statistical model performs quite well, explaining about 90% of the variance (pseudo R^2 Nagelkerke of 0.90).

The suitability of a cell for a certain land-use type, in most cases, is positively correlated with the occurrence of the same land-use type in its immediate surroundings. The suitability for nature, for example, increases with 0.77 for every nature cell in the first ring (denoted in the table with Nature1_1). A negative correlation is observed for the probability of nature, with the presence of residential land in the first ring. The opposite is true for the relation with the land use in the second and third ring. Here, identical land uses seem to repel rather than attract each other. The probability of residential land, for example, decreases slightly with the presence of residences in ring 2 and 3, yet it increases a little with the presence of agricultural land use. These unexpected relations may be interpreted as small corrections for the strong correlation with these land-use types in ring 1. The estimate for recreation differs considerably from the other types of land use, in the sense that neighbouring recreational land use did not produce a significant result. This may be caused by the limited number of recreation observations and by the fact that recreation occurs in smaller spatial clusters. Please note that 11 of the total of 27 possible variables, related to neighbouring land-use types, are not included in the presented regression results, as they did not produce statistically significant results. The suitability values of the reference category (agriculture) were set to zero.
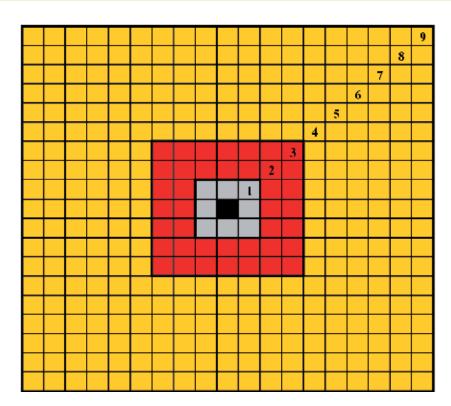
3.3 Map Comparison

To compare the maps of the different model runs, simple cell-to-cell comparisons of simulated and observed land use are used, in either 1993 (calibration) or 2000 (validation). These comparisons are made for all simulated land-use types separately, to individually assess their performance. An overall degree of correspondence for the whole simulation has not been calculated, as this would be largely equal to the value of the prevailing land-use type (agriculture). The selected, straightforward comparison approach is easy to comprehend and very informative. Other, more complex comparison methods that deliver, for example, (Fuzzy)Kappa statistics or log-likelihood values (De Pinto and Nelson, 2006; Hagen, 2003; Munroe and Muller, 2007; Pontius Jr. et al., 2004; Visser and De Nijs, 2006), are more difficult to interpret and, therefore, have not been applied. Application of a comparison method that looks beyond single cells and includes corre-

Variable	Nature	Residential	Commercial	Recreation
Intercept	0.7706	-3.3650	-3.7536	5.1984
Nature1_1	0.7963	-0.1407	-0.1000	-1.4175
Nature2_3	-0.2540	0.0475*	0.0587	0.1220
Railways1_1	-0.0473*	0.0803	0.2381	-1.6381
Nature4_9	0.0776	0.0526	0.0521*	0.2915
Agriculture1_1	-0.6593	-0.7555	-0.8047	-2.2313
Agriculture2_3	0.0785	0.1400	0.1358	0.2340
Train_station_8	-0.0054	0.0147	0.0205	-0.0026
Water1_1	0.0182*	-0.0596*	0.1283	-1.0516
Water2_3	-0.0377*	0.0482*	0.0398*	0.1645
Water4_9	0.0463	0.0240	0.0027*	0.1106
Main_road1_1	0.0134	0.0130	0.0673	-1.1861
Commercial1_1	0.0120	0.4834	1.5463	-1.3763
Other1_1	-0.0190	-0.2064	-0.097*	-1.5135
Commercial2_3	-0.0099	-0.0355	-0.2875	-0.0439
Infra2_3	-0.0272*	-0.0091*	0.0578	-0.9471
Residential1_1	-0.0409	1.1302	0.3943	-1.3621
Residential2_3	0.0192*	-0.1304	0.0612*	0.1317
EMS1990	2.8759	-1.4135	-1.1231	-1.4839
Natura 2000	-0.3400	-0.5079	-0.2611	-0.6873

Note: all variables are significant at the 0.05 level unless indicated with an asterisk.

The three sets of rings (1, 2-3 and 4-9) surrounding the central observation point, which are used as explanatory variables in the multinomial logistic regression.

spondence in neighbouring cells (such as the FuzzyKappa statistic) is likely to produce better results. We do not consider this appropriate in our case, however, as we explicitly include reference to the current state of the neighbouring cells in the suitability map definition. Calculating a degree of correspondence that would incorporate this information would,

thus, artificially increase the observed match and, moreover, obscure the exact performance of the model.

For the discrete model that contains homogenous cells the share of simulated cells that corresponds to the observed land use is calculated per land-use type. While interpreting these values, it is important to note that the observed land use is not necessarily true or correct, as was discussed previously in Section 3.1 For the continuous model, two methods were used to compare the maps. One is identical to the method used to compare the discrete maps, and compares the dominant land use of the result map with the original map of dominant land-use. The other method is slightly more complex and compares the ratios of simulated and observed land use per cell as follows:

$$C_j = \frac{\sum_c |M_{cj} - O_{cj}|/2}{\sum_c O_{cj}} \qquad (4)$$

where:

C_j is the degree of correspondence for land-use type j;

M_{cj} is the simulated amount of land in cell c for land-use type j;

O_{cj} is the observed amount of land in cell c for land-use type j.

In this case, observed land use is also described as a fraction, based on an aggregation of the 16 original grid cells from the 25-metre grid base map that comprise the 100-metre grids. Subsequently, all these differences are added up and this total allocation difference is used to calculate the share of correspondence as part of the total allocated area. Because the exact (observed) quantities of land use have been used in the calibration and validation, the surplus of allocated land in one cell corresponds with a deficit in other cells. This implies, of course, that the total of all differences equals zero and, therefore, the absolute values of these differences are to be summed. As a result, single allocation differences are considered twice and, therefore, we divide the total of the observed errors by two. The resulting share of correspondence equals 100% when the amount of allocated land is equal to the observed amount in every cell. Conversely, the share equals zero when none of the allocated amount of land is present in the corresponding cells with observed land use. If we would have considered all allocation differences here without dividing them by two, the share of correspondence could theoretically range from 100% to -100%. The applied comparison method has the additional advantage of producing a degree of correspondence that is fairly comparable to the one calculated for the discrete model. In fact, the method would produce identical results when the continuous model would only simulate fractions of 0% or 100% per cell.

The so-called exogenous land-use types whose locations are fixed by the model (water, infrastructure and exterior) are not included in the calibration and validation of the model. The main reason for this is that calibrating these land-use types is futile as the model does not attempt to simulate

their dynamics. Including these land-use types would, in fact, provide an overly positive impression of the performance of the model, as these types of land use are extremely static and cover 62% of the total model area; simulating no change for these categories, thus, guarantees a strong degree of correspondence between simulated and observed land use. For the present calibration and validation exercise this means that only cells which are completely filled with endogenous land use in 1993, as well as in 2000, have been compared. This has the additional advantage of discarding many of the grid cells where a change in classification methodology suggests changes in observed land use that did not actually occur. This refers, in particular, to those locations that were classified as infrastructure in 1993 and as something else in 2000, as was discussed in Section 3.1 The rare occasions were exogenous land has indeed changed (e.g. infrastructural developments or water reclamation) are, thus, excluded from the analysis. However, in actual model applications, such changes are supplied exogenously to the simulation following existing plans. This, generally, relates to infrastructure development schemes that are typically planned many years before their actual realisation. Therefore, these are relatively easy to incorporate in simulations of future land use.

Calibration results

Section 4 describes the results of the calibration of the Land Use Scanner. The merits of these calibration efforts are tested by comparing the resulting simulations with the initial 1993 land use. The first and most simple effort only takes the actual (1993) land use as an indication of suitability, and then uses the allocation algorithm to reconstruct these land-use patterns. This very basic test is included, to analyse whether the model is capable of exactly reproducing current land use. The second and actual calibration effort uses the results from the multinomial logistic (MNL) regression analysis, to describe the probability that a certain land-use type will occur. These probabilities are estimated, using a random set of observations that consists of about 1.600.000 cells, representing about half of the total number of observations. The other half of the cells is used as an independent set that allows us to test validity of the observed relations.

4.1 Discrete model

4.1.1 1993 land use as input
This simple calibration effort is carried out by using the actual land use (1993) as input. In this approach, the suitability value of a specific land-use type is set to either '1', when this type of use is present in 1993, or '0' when another type of land use is present. The allocation results show, as is to be expected, complete similarity to the input. Table 4.1 expresses this similarity as the percentage of identical cells for the whole country. Figure 4.1 shows a graphical representation of the results for the area around Amsterdam. The results prove that the allocation method itself works properly.

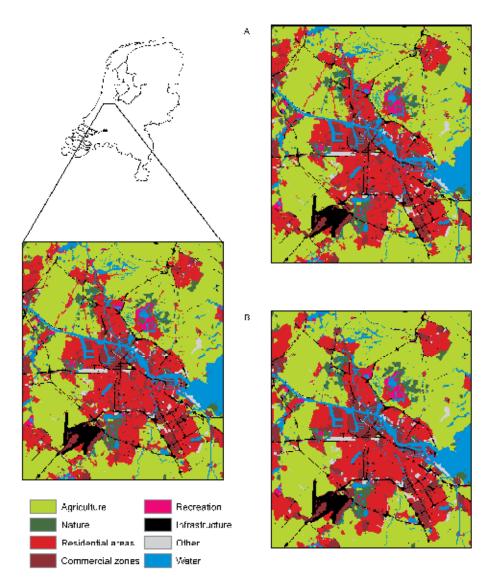### 4.1.2 Multinomial regression specification
In this calibration effort, the suitability values depend on the results of the multinomial regression analysis. The comparison of the resulting simulations with the original (1993) land use is presented in Table 4.1. Agriculture is especially well simulated, with 97% of the cells in the correct position. For commercial land and recreation, the simulation performs less well, with 65 to 70% of the cells positioned correctly. The results are almost equal for the calibration and the independent data set, indicating that the observed relations hold true for the whole country. Figure 4.1B shows how well the patterns correspond in the Amsterdam area. The simulated land-use patterns are slightly smoother than the original land use. The only areas that are not reproduced in the simulation are those that consist of relatively few adjacent cells (small parks or extremely elongated villages). Such results are inherent to the applied method and are also found in other applications of multinomial regression analysis that strongly rely on neighbouring land use (Dendoncker et al., 2007). While assessing these results, it is important to note that the simulation is performed on a blank map, and that no information related to actual land use in the cell is used. The results, thus, indicate that most land-use types are strongly related to the surrounding land use. Or, phrased differently, land-use types tend to cluster in areas that are typically (much) larger than the resolution of the model. The fact that recreation and commercial areas are less well simulated, most likely, also can be attributed to the fact that these typically occur in smaller spatial clusters than agriculture or nature. Our methodology with its focus on neighbourhood relations has difficulty in reproducing these land-use types.

Comparison of the calibration efforts with the observed 1993 land use

Table 4.1

Simulated land use in 1993		Agriculture	Nature	Residential	Commercial	Recreation
Discrete model						
1993 land use	complete data set	100.0%	100.0%	100.0%	100.0%	100.0%
Full MNL	calibration data set	97.0%	92.0%	81.3%	65.8%	70.1%
	independent data set	97.0%	92.0%	81.2%	65.6%	69.2%
Continuous model						
1993 land use	complete data set	99.5%	99.2%	99.1%	98.2%	97.9%
Full MNL (dom.)	calibration data set	97.5%	93.3%	79.4%	58.5%	66.6%
	independent data set	97.4%	93.3%	79.2%	58.2%	65.9%
Full MNL (ratio)	independent data set	95.5%	91.8%	83.7%	75.1%	78.2%

Note: the figures indicate a percentage of correspondence based on a cell-by-cell comparison. A differentiation for the calibration and independent data set is made where applicable.

Observed 1993 land use (left) and its simulation with the discrete model, using 1993 land use as input (A) and the multinomial regression specification (B) as input for the suitability maps.
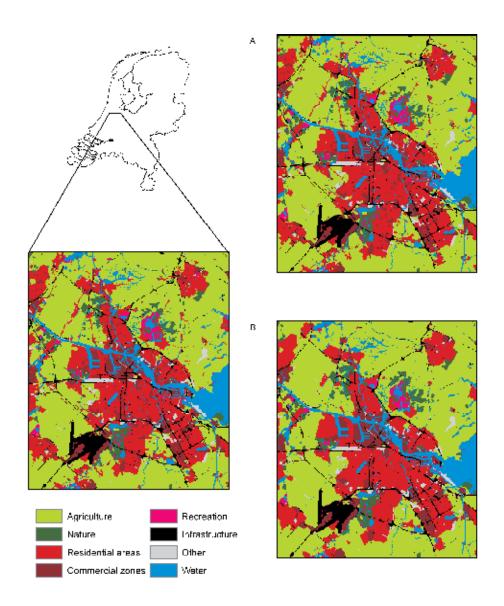
4.2 Continuous model

4.2.1 1993 land use as input

To use the 1993 land use as input for the continuous model, the per-cell suitability value of each land-use type is specified, as the natural logarithm (ln) of the area claimed by that land use in that particular cell. This definition corresponds with the original algorithm described in Section 2.1. The approach leads to an exact representation of the 1993 land use (Table 4.1), showing that the continuous model, just as the discrete model, is working properly. The map resulting from these simulations (Figure 4.2A) also shows this correspondence. Please note that two different types of comparison are used for the continuous model. The first type compares maps of dominant land-use, for both observed and simulated land use. This approach is identical to the one used for the discrete model, but has the disadvantage of over- or underestimating the presence of certain land-use types. The second comparison, therefore, relates to the actual quantities (or ratios) of land use, per cell (See the map comparison description in Section 3, methodology).

4.2.2 Multinomial regression specification

The second calibration attempt uses the results from the multinomial regression analysis presented in Section 4.1.2. A comparison with the observed land-use quantities (Table 4.1) shows that the continuous model performs reasonably well, with a correspondence of 58% to 97%. This result is remarkable, considering that the statistical analyses were performed on the discrete data sets, rather than the continuous data set

Observed 1993 land use (left) and its simulation with the continuous model, using 1993 land use (A) and the multinomial regression specification (B) as input for the suitability maps.

that underlies this specific allocation model. While assessing these results, it is important to note that an allocation surplus in one cell, essentially, leads to a deficit in another (see the discussion in the Methodology Section). When the actual ratios are compared, it becomes clear that, according to this comparison method, the model performs a little better with an overall correspondence of 75-95%. This mainly shows the varying impact of using a different data representation method. For some land-use types (e.g. agriculture) the fractional comparison performs less well, while for others (notably commercial and recreation) it suggests a better correspondence. The latter types of land use may be structurally under-represented in maps of dominant land-use, as they tend to cover only small areas.

The level of correspondence is also exemplified by the related map of dominant land use presented in Figure 4.2B: only marginal differences to the observed 1993 land use occur. These differences relate to the presence of slightly more compact forms, as was also the case with the simulation following the discrete model.

Validation results

5

The validation results are described in the same way as the calibration results. The performance of the two different model versions is tested by comparing the simulation results for 2000 with the observed land use for that year. The first and most simple effort only takes the actual (1993) land use as an indication of suitability, whereas the second and actual calibration effort uses the results from the multinomial logistic (MNL) regression analysis, to describe the probability that a certain land-use type will occur. Note that this statistical analysis refers to the 1993 land-use patterns. As with the discussion on the calibration results, a distinction is made between the randomly selected calibration data set that was used for the specification of the logistic regression model and the independent data set that allows us to test validity of the observed relations.

To focus the comparison on the impact of the suitability map definition, the exact quantities per land-use type corresponding to the 2000 situation are used. The regional land-use claims, thus, correspond exactly with the quantities of observed land use in 2000. An important aspect that especially influences the validation attempt, is the strong decrease in infrastructure between 1993 and 2000 in the observed land use. Since this is treated as an exogenous class in the model, the simulation preserves the 1993 patterns in the simulation. However, this implies that the locations where infrastructure disappears will be filled by other land-use types in the 2000 simulation. In this case, the model has been given the liberty to allocate more agricultural land if needed, thus causing a deliberate mismatch between the total amount of allocated agricultural land, and the original demand derived from the observed 2000 land use. This methodological inconsistency in the base data does not influence the validation results as all cells that belonged to any of the exogenous classes in the observed land use of 1993 or 2000 (water, infrastructure or exterior accounting for 62% of the total modelled area), are left out of the analysis of correspondence. This is discussed in more detail in Section 3.3

5.1 Discrete model
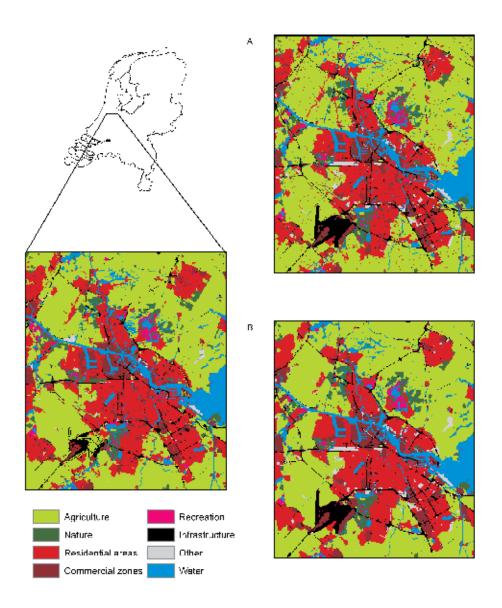
5.1.1 1993 land use as input
When the 1993 land use is used as input for the 2000 simulation, 84% to 98% of the cells per land-use type is correctly simulated (Table 6). This decrease in the share of correctly predicted cells, compared to the similar calibration effort

(Section 4.1.1) was to be expected. The decrease can partly be attributed to the inconsistencies in the available base date (as was discussed in Section 3), and is furthermore attributable to the applied method. By only relying on current land use as an indication of suitability, the model is not offered any specification on where to allocate the changed land use. No information is available on the suitability of the additional locations needed to accommodate the increase in, for example, residential or commercial land use. This is clearly illustrated with the map that presents the simulated land use for 2000 (Figure 5.1A). The relatively large increase in residential land use is allocated in an apparently random pattern. This randomness is related to the identical suitability values of all cells, other than those for which residential land was the original use. To find a solution to the allocation problem in these cases with insufficient variation in the suitability values, the model adds an infinitely small value to the suitability definition. These so-called simulated perturbations only influence the simulations when a lack of variation in the original suitability values prevents the allocation algorithm to find a solution. The perturbations are the product of the cell numbers and the infinitely small values. This would cause an artificial clustering of land use, as the cell numbers are structured across space. Therefore, all cells selected for allocation are placed in a pseudo-random sequence, in such a way that the (original) cell numbers do not influence the allocation. In this way, the formation of undesirable clusters is presented, and the random pattern mentioned earlier emerges. It should be noted, however, that these simulated perturbations only impact the simulation when the suitability definition has insufficient variation. This does not normally happen in model applications as the suitability definition usually consists of many different spatial data layers that provide a strong degree of spatial variation.

5.1.2 Multinomial regression specification
The simulation for 2000, which follows the logistic regression, performs slightly less well than the validation attempt which used the 1993 land use as input (Table 5.1). The scores for the calibration and independent data sets are almost identical, as was the case with the calibration results. This shows that the obtained statistical relations are equally valid for the particular part of the land-use data set for which they were estimated, and for the remaining part.
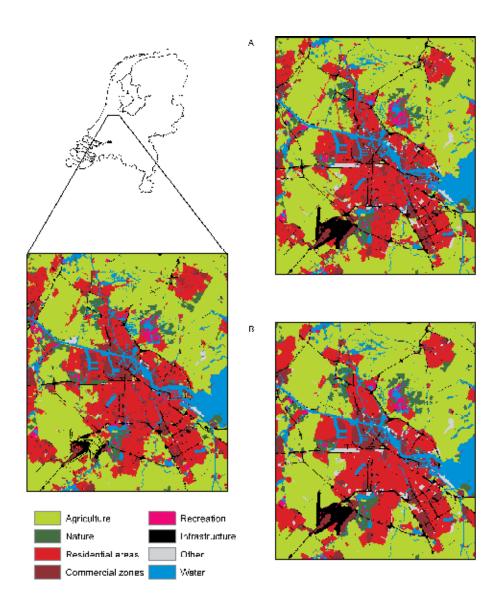
That the validation based on the regression analysis performs less well than the one based solely on the 1993 land use, can

Agriculture   Recreation
Nature   Infrastructure
Residential areas   Other
Commercial zones   Water

Observed 2000 land use (left) and its simulation with the discrete model, using 1993 land use as input (A) and the multinomial regression specification (B) as input for the suitability maps

be explained by the fact that this attempt includes a partially incorrect simulation of the land use that remains the same (as was discussed in 4.1.2) and, in addition, will only simulate a small part of the changed cells correctly. The latter may be due to the fact that the applied logistic regression relies strongly on land use in neighbouring cells. Therefore, new urban developments are attached in the form of small rings around current urban areas, producing compact urban forms (Figure 5.1B). This process is intensified by the simultaneous conversion of small open areas within the urban fabric. This approach, therefore, is not well suited to simulate the development of the large contiguous areas at specific, pre-defined locations, which is the typical result of Dutch planning, as discussed in Section 3. It is clear that these developments,

which so unmistakably follow the Dutch planning process, can be simulated much better through the inclusion of specific spatial planning maps. That agriculture and, to a lesser extent, nature are simulated with a higher degree of correspondence may partly be attributed to the fact these land-use types typically cover large areas that can be captured, more easily, with our methodology that stresses neighbourhood relations. Another explanatory factor may be that the amount of change in these categories relative to the area covered in 1993 (about 1% for agriculture and 4% nature) is fairly small, compared to the urban and recreational types of land use (9 and 8%, respectively). Previous calibration efforts have shown that models that predict little change generally perform

Observed 2000 land use (left) and its simulation with the continous model, using 1993 land use as input (A) and the multinomial regression specification (B) as input for the suitability maps

better than the models that simulate a lot of change (Pontius Jr. et al., 2008).

Another factor which influences the simulation outcome, is the fact that a static analysis of land-use patterns has been performed at one moment in time. No information on land-use change was included in the analysis. The analysis of recent changes, rather than the long-term historical development of the current land-use pattern, may offer useful clues for pinpointing the location factors, which help explain changes in the near future. Therefore, future calibration research will include an analysis of changed land use, and will incorporate specific maps related to, for example, municipal building

plans. In fact, most Land Use Scanner applications include a wide range of spatially explicit policy and planning maps.

5.2 Continuous model

5.2.1 1993 land use as input
When the 1993 land use is used as input for the 2000 simulation, 84% to 99% of the cells per land-use type can be correctly simulated (Table 6). A score that is comparable to the validation results of the discrete model, discussed before. The related map of dominant land use (10A), in contrast, better resembles the observed land use. This is mainly caused by the lack of scattered residential areas, which were described in

Simulated land use in 2000		Agriculture	Nature	Residential	Commercial	Recreation
Discrete model						
1993 land use	complete data set	98.6%	92.7%	85.5%	83.9%	84.3%
Full MNL	calibration data set	95.9%	89.0%	80.1%	58.4%	61.5%
	independent data set	95.9%	89.0%	80.2%	58.4%	61.3%
Continuous model						
1993 land use	complete data set	98.6%	92.7%	85.5%	83.9%	84.3%
Full MNL (dom.)	calibration data set	96.7%	89.5%	76.8%	52.3%	58.5%
	independent data set	96.7%	89.5%	76.7%	52.0%	58.4%
Full MNL (ratio)	independent data set	95.5%	89.9%	82.9%	72.3%	73.1%

Note: the figures indicate a percentage of correspondence based on a cell-by-cell comparison. A differentiation for the calibration and independent data set is made where applicable.

Section 5.1.1. This indicates an interesting difference between the two allocation algorithms. In the absence of sufficient suitable locations for the land-use types that claim extra space, the discrete model allocates complete cells in an apparent random way, whereas the continuous model will only slightly increase the allocated amount of land. The latter does not show on the maps of dominant land use.

5.2.2 Multinomial regression specification

The simulation for 2000, which follows the logistic regression, performs less than the previous validation attempt (Table 5). The map showing the dominant land use related to this calibration effort (Figure 10B), shows that the logistic regression, especially, misses the relatively large-scale planed urban and nature extensions. These findings correspond to the validation of the discrete model. As with the other model version, the performance of the calibration and independent data sets is identical. Compared to the discrete model version, the continuous model seems to perform slightly less well.

Discussion

6

The main objective of most Dutch planning-related Land Use Scanner applications is to provide plausible spatial patterns related to predefined conditions that typically follow from scenario-based assumptions or policy objectives. This calibration and validation analysis, therefore, focuses on the spatial performance of the model and more specifically aims to:

1. assess the potential of the new fine resolution in producing sensible land-use patterns; and
2. compare the performance of the two available allocation algorithms.

The calibration exercise, furthermore, intends to pinpoint some of the most important location factors that have produced the current land-use patterns. The findings of this study, in relation to these objectives, are discussed below. Furthermore, we discuss some additional, more conceptual validation issues and options for further research.

6.1 Providing sensible spatial patterns

The sensibility of the simulated land-use patterns is expressed as the degree to which these correspond to the observed land-use patterns. The initial calibration exercise that uses the current (1993) land use as an indication of land-use suitability, proves that the model is able to exactly reproduce existing land-use patterns. This shows that the allocation procedure is working correctly; for each land-use type the proper amounts and locations are used. In this respect, it is interesting to note that simulation starts with an empty map. The simulation reproduces current land use, by properly describing suitable locations, not through fixing land uses at their present location as other models do. This has the important advantage of making the model extremely flexible in producing simulations of future land use. This characteristic makes the model very suited to simulate the land-use patterns that may result from specified scenario conditions or policy objectives. When these conditions are properly quantified in terms of amount and location, the model will be able to simulate the corresponding spatial patterns. The exact reproduction of current land use, furthermore, shows that numerical diffusion does not occur when suitability maps are properly defined. This issue refers to the occurrence of land use that is too diffuse or spread out, and was observed in previous applications of the continuous model when suitability maps were not pronounced enough (see De Regt, 2001).

The validation results relating to the statistically derived suitability maps show that the model performs relatively well in simulating agricultural land use and nature. For the more urban categories (recreation, residential and commercial land use), the models performs less well. This may partly be due to limitations of the applied statistical analysis that relies heavily on neighbourhood relations. This focus limits the possibility to properly simulate land-use types that cover relatively small and erratic areas as, especially, recreation and commercial land use do. Inclusion of more detailed and more specific explanatory variables (related to, for example, spatial planning and accessibility) and a focus on the explanation of recent land-use changes may help improve the performance of the model in this respect. Another factor explaining the relatively high degree of correspondence for agriculture and nature may be that the amount of change in these categories is relatively small, compared to the urban and recreation types of land use. An extensive analysis of calibration efforts has shown that models that predict little change, generally, perform better (Pontius Jr. et al., 2008).

While assessing the performance of the model, it is important to consider that the currently used data sets with observed land use contained several inconsistencies. We find that 36% of the observed land-use changes may be due to methodological inconsistencies. This may have caused an erroneous assessment of the degree of (dis)correspondence between simulated and observed land use, but, more fundamentally, may also have led to misspecifications in the statistical analysis that underlies the presented calibration and validation.

On a more fundamental level, however, it is clear that socio-economic developments will always have a large degree of uncertainty. Not even the most rigorous calibration offers any guarantee of producing the 'right' simulations of future land use. To cope with this large degree of uncertainty, most socio-economic outlooks on the future, therefore, apply the scenario method. It is important to recall that the main objective of the Land Use Scanner is to produce sensible land-use patterns that correspond to such predefined scenario conditions. This implies that the model neither has to replicate past developments, nor has to produce the most probable land-use pattern. First and foremost, it should be able to produce possible spatial patterns that match the anticipated future conditions set out in scenarios or spatial policy objectives. And, as was discussed above, the model is indeed well-suited to do just that. Furthermore, this means that the outcomes of

the model should not be interpreted as fixed predictions for particular locations, but rather as probable spatial patterns. The land-use simulations, thus, provide spatial impressions of the future that are helpful in discussions on spatial developments and related policy interventions. This type of application resembles the spatial designs that are typically produced by landscape architects, but differs in the sense that it is more bound in quantitative constraints and socio-economic causality. The (dis)similarities of the modelling and designing methods to produce simulations of future land use are discussed extensively, elsewhere (Groen et al., 2004).

6.2 Comparing the two allocation algorithms

The relative performance of the individual algorithms can be assessed by comparing the degree to which the respective simulation outcomes correspond to the observed land-use patterns. The validation shows that the two allocation mechanisms, given equal starting points, provide very similar land-use patterns. The discrete algorithm seems to produce a slightly higher degree of correspondence with the observed land use, but it has to be stressed, that different comparison methods have been used and the values cannot be directly compared. Furthermore, the regression analysis has been performed on the discrete data set, which may also have caused the higher similarity to the discrete model. The similarity of the modelled and observed land use for both methods is such, that we consider the discrete algorithm equally suitable for allocation as the continuous model.

The new discrete allocation method proved to be very powerful in solving the very large optimisation problem at hand. The applied algorithm finds an exact solution with a desktop PC within several minutes, provided that a feasible solution exists. This calculation time is comparable to the original continuous model. This is an impressive result, as we do not know comparable complex optimisation models that are able to provide such fast results.

In addition, we like to stress that ▯ from a theoretical perspective ▯ the two approaches are also more alike than is initially apparent. Section 2.2 discusses this more extensively and states that the models will yield identical results when the importance of the suitability values in the continuous model would be infinitely large. This is not possible in practice because of computational limitations, but the present validation indicates that simulation results are indeed fairly similar when equal starting points are chosen.

6.3 Pinpointing the most important location factors

The calibration exercise also intends to pinpoint some of the most important location factors that produce current land-use patterns and reveal their relative weights. In the present research, current land-use patterns and, especially, the presence of a similar land-use type in the neighbouring cells, proved to be an important component in describing the suitability of locations for most land-use types. This indicates the importance of spatial autocorrelation in (Dutch) land-use

data sets. However, it should be noted, that the current study estimated these relations in a static (one year only) regression analysis, and tested them over a short, seven-year period. Other factors may prove to become more important when land-use changes are analysed and tested for a longer period of, for example, several decades.

6.4 Additional validation aspects

The current calibration and validation study focuses on the ability of the model to provide sensible spatial patterns and does not consider additional modelling aspects that influence the simulation results. These relate, first and foremost, to the amount of land-use change that is used in simulations and, more general, to the complete modelling chain in which the Land Use Scanner is applied. Both aspects are briefly discussed below.

The amount of land-use change that is fed into the model directly influences simulation outcomes. For this information the Land Use Scanner relies on external sources. These are, typically, sector-specific models, from specialised consultancy firms and research institutes, of the future demand for residential, commercial and government intentions, expressed in policy documents for recreation and nature. These external sources offer the best available information on sector-specific developments and are included in the modelling chain to incorporate as much specialist knowledge as is possible. In fact, integrating sector-specific knowledge on spatial developments, often available on a regional scale, and allocating this to the local grid-cell level, can be considered one of the main features of the Land Use Scanner. In this respect, the model differs from many other comparable models that also aim to forecast the dimension of land-use change.

The main drawback of relying on these independent sources, however, is that their mutual consistency is not guaranteed. Inconsistencies related to the included base data, applied methodologies or (scenario-based) assumptions are possible, as was also suggested at the international audit of the Land Use Scanner and Environment Explorer models (Timmermans et al., 2007). A previous study specifically looked at the external input sources in the land-use modelling chain and concluded that proper documentation is lacking to assess these possible inconsistencies (Dekkers and Koomen, 2006). Specific model-applications were often poorly documented and no descriptions were found of the harmonisation of modelling assumptions. Land Use Scanner applications often hint at this mismatch when they show that the total demand for land that arises from the different sector-specific sources exceeds the total amount of available land. The model signals this deviation and allows the modellers to revise the sector-specific demand or pinpoint a land-use type (normally agriculture) that will have to provide more space. Application of the Land Use Scanner, thus, helps to clarify part of the choices that have to be made in relation to future spatial developments.

Concerns about the consistency of the simulation outcomes can also be expressed in relation to the full modelling chain.

This chain includes the construction of scenarios, the model-ling of sector-specific developments, the spatial integration and allocation in the Land Use Scanner and, finally, the assess-ment of various, often environmental, impacts in dedicated tools and models. Each of these subsequent phases may introduce additional assumptions, data layers, uncertainties and errors that undermine the quality of the results. A full assessment of this issue is beyond the scope of the current analysis. The model improvement project that the Nether-lands Environmental Assessment Agency started in 2008, however, does pay attention to this and other more concep-tual modelling issues.

6.5 Further research

Based on the current research we can make several recom-mendations for further research related to: the quality of the base data, the focus of the explanatory statistical analysis and the consistency of the modelling chain in which the Land Use Scanner is applied.

For any further study on land-use change it is highly rec-ommended that the quality of the land-use base data is improved. The data sets that we applied stretched over a relatively short time period, but they already show consider-able classification differences and other sources of error. Data sets covering the longer periods needed to perform a more fundamental calibration, are known to contain even larger methodological inconsistencies and, thus, require additional efforts in data preparation.

To refine the current explanatory statistical analysis that underlies the calibration of the land-use allocation algorithms, further research should focus on longer time periods and the actual land-use changes that occur. By using a longer time period, it becomes possible to see whether the importance of certain location factors changes over time and, thus, to assess the robustness of the observed statistical relations. An analysis of change in land-use patterns, rather than explain-ing current configurations, is especially interesting as it offers the possibility to implement transition costs into the model. Such transition costs can help to improve the performance of the model. They can also be estimated in a multinomial logistic regression analysis, but require the availability of a third intermediate time-step in the base date (e.g. 1996), to be able to calibrate the model on one period (year 1-year 2) and validate it on another subsequent period (year 2-year 3). Further statistical analysis could benefit from the incorpora-tion of additional independent variables. Previous research (Verburg et al., 2004) included, for example, the distance to historic city centres. The inclusion of detailed municipal plans for additional roads or residential areas, and related more general spatial planning maps, will be incorporated in future analyses of land-use changes.

■

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Acknowledgements

Calibration and validation of the Land Use Scanner allocation algorithms

The Land Use Scanner is a spatial model that simulates future land use. Since its initial development in 1997, it has been applied in a large number of policy-related research projects. In 2005, a completely revised version became available that allows land use to be modelled at a finer 100 metres resolution. This new version also offers the possibility to model homogenous cells (containing only one type of land use) in addition to the heterogeneous cells that were already available in the previous, coarser version. Each approach uses its own algorithm to allocate land-use types to individual cells.

This report describes both algorithms and assesses their spatial allocation performance. The two model algorithms are calibrated using multinomial logistic regression and validated by applying the calibrated suitability definition in a subsequent time period. The validation indicates that both model algorithms provide sensible spatial patterns. In fact, the two different modelling approaches produce very comparable results, given equal starting points. In general, we conclude that the model is well-suited to simulate possible future spatial patterns in the scenario or policy-optimisation studies that are typically carried out by the Netherlands Environmental Assessment Agency.