Modelling Land-Use Change

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Modelling Land-Use Change

Progress and Applications

Edited by

ERIC KOOMEN

Department of Spatial Economics/SPINlab,
Vrije Universiteit Amsterdam,
The Netherlands

JOHN STILLWELL

School of Geography,
University of Leeds,
United Kingdom

ALDRIK BAKEMA

Netherlands Environmental Assessment Agency,
Bilthoven, The Netherlands

and

HENK J. SCHOLTEN

Department of Spatial Economics/SPINlab,
Vrije Universiteit Amsterdam,
The Netherlands

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Contributing authors

Antonio Aledo, Departamento de Sociología y Teoría de la Educación, Universidad de Alicante, Ap. Correos 99, 03080 Alicante, Spain. E-mail: antonio.aledo@ua.es

Eyal Ashbel, Department of Geography, Hebrew University of Jerusalem, Mount Scopus, 91905 Jerusalem, Israel. E-mail: eashbel@netvision.net.il

Aldrik Bakema, Netherlands Environmental Assessment Agency (MNP), PO Box 303, 3720 AH Bilthoven, The Netherlands. E-mail: aldrik.bakema@mnp.nl

José I. Barredo, Land Management and Natural Hazards Unit, Joint Research Centre of the European Commission (JRC), TP 261, I-21020 Ispra, Italy. E-mail: jose.barredo@jrc.it

Michael Batty, Centre for Advanced Spatial Analysis (CASA), University College London, 1-19 Torrington Place, London WC1E 6BT, United Kingdom. E-mail: mbatty@geog.ucl.ac.uk

Juan Bellot, Departamento de Ecología, Universidad de Alicante, Ap. Correos 99, 03080 Alicante, Spain. E-mail: juan.bellot@ua.es

Adi Ben-Nun, Department of Geography, Hebrew University of Jerusalem, Mount Scopus, 91905 Jerusalem, Israel. E-mail: bennun@cc.huji.ac.il

Patrick Bogaert, Département d'Agronomie, Université Catholique de Louvain, Place Croix du Sud 2, B-1348 Louvain-la-Neuve, Belgium. E-mail: bogaert@enge.ucl.ac.be

Andreu Bonet, Departamento de Ecología, Universidad de Alicante, Ap. Correos 99, 03080 Alicante, Spain. E-mail: andreu@ua.es

Judith Borsboom-van Beurden, Netherlands Environmental Assessment Agency (MNP), PO Box 303, 3720 AH Bilthoven, The Netherlands. E-mail: judith.borsboom@mnp.nl

Matthias Bürgi, Research Unit of Land Use Dynamics, Swiss Federal Research Institute (WSL), Zürcherstrasse 111, 8903 Birmensdorf, Switzerland. E-mail: matthias.buergi@wsl.ch

Giancarlo Carrai, SVALTEC S.r.l., Via del Campofiore 106, 50136 Florence, Italy. E-mail: gc.carrai@svaltec.it

João Corte-Real, Centro de Geofísica de Évora e Departamento de Física da Universidade de Évora, Rua Romão Ramalho, 59, 7000 Évora, Portugal. E-mail: jmcr@uevora.pt

Jasper Dekkers, Department of Spatial Economics/SPINlab, Vrije Universiteit, De Boelelaan 1105, 1081 HV, Amsterdam, The Netherlands. E-mail: jdekkers@feweb.vu.nl

Nicolas Dendoncker, Département de Géographie, Université Catholique de Louvain, Place L. Pasteur 3, B-1348 Louvain-la-Neuve, Belgium. E-mail: dendoncker@geog.ucl.ac.be

Tomaz Dentinho, Gabinete de Gestão e Conservação da Natureza, Departamento de Ciências Agrárias, Universidade dos Açores, 9701-851 Angra do Heroísmo, Portugal. E-mail: tomaz.dentinho@mail.angra.uac.pt

Denise Eisenhuth, Departamento de Ecología, Universidad de Alicante, Ap. Correos 99, 03080 Alicante, Spain. E-mail: d.m.eisenhuth@ua.es

Guy Engelen, Centre for Integrated Environmental Studies, Flemish Institute for Technological Research (VITO), Boeretang 200, BE-2400 Mol, Belgium. E-mail: guy.engelen@vito.be

Dick Ettema, Faculty of Geosciences, Utrecht University, PO Box 80115, 3508 TC Utrecht, The Netherlands. E-mail: d.ettema@geo.uu.nl

Daniel Felsenstein, Department of Geography, Hebrew University of Jerusalem, Mount Scopus, 91905 Jerusalem, Israel. E-mail: msdfels@mscc.huji.ac.il

Chang-Chun Feng, Center of Real Estate Research and Appraisal, Peking University, Rm. 3273, Bld. Yifuerlou, 100871 Beijing, China. E-mail: fcc@urban.pku.edu.cn

Naftali Goldshlager, Soil Erosion Station, Israeli Ministry of Agriculture, Ruppin Institute, Post. Emek-Hefer 40250, Israel. E-mail: gold_n@macam.ac.il

Joana Gonçalves, Gabinete de Gestão e Conservação da Natureza, Departamento de Ciências Agrárias, Universidade dos Açores, 9701-851 Angra do Heroísmo, Portugal. E-mail: joanagoncalves78@gmail.com

Dagmar Haase, Department of Applied Landscape Ecology, Centre for Environmental Research (UFZ), Permoserstrasse 15, D-04318 Leipzig, Germany. E-mail: dagmar.haase@ufz.de

Stephen Hallett, National Soil Resources Institute, Cranfield University at Silsoe, MK45 4DT Bedfordshire, United Kingdom. E-mail: s.hallett@Cranfield.ac.uk

Anna M. Hersperger, Research Unit of Land Use Dynamics, Swiss Federal Research Institute (WSL), Zürcherstrasse 111, 8903 Birmensdorf, Switzerland. E-mail: anna.hersperger@wsl.ch

Peter Heuberger, Netherlands Environmental Assessment Agency (MNP), PO Box 303, 3720 AH Bilthoven, The Netherlands. E-mail: peter.heuberger@mnp.nl

Annelie Holzkämper, Department of Applied Landscape Ecology, Centre for Environmental Research (UFZ), Permoserstrasse 15, D-04318 Leipzig, Germany. E-mail: annelie.holzkaemper@ufz.de

Louisa J.M. Jansen, Land/natural resources consultant, Via Girolamo Dandini 21, 00154 Rome, Italy. E-mail: Louisa.Jansen@tin.it

Kor de Jong, Faculty of Geosciences, Utrecht University, PO Box 80115, 3508 TC Utrecht, The Netherlands. E-mail: k.dejong@geo.uu.nl

Eric Koomen, Department of Spatial Economics/SPINlab, Vrije Universiteit, De Boelelaan 1105, 1081 HV, Amsterdam, The Netherlands. E-mail: ekoomen@feweb.vu.nl

Mario Köstl, Austrian Research Centers - ARC Systems Research GmbH, Donau-City-Strasse 1, 1200 Vienna, Austria. E-mail: mario.koestl@arcs.ac.at

Marianne Kuijpers-Linde, Netherlands Environmental Assessment Agency (MNP), PO Box 303, 3720 AH Bilthoven, The Netherlands. E-mail: marianne.kuijpers@mnp.nl

Carlo Lavalle, Land Management and Natural Hazards Unit, Joint Research Centre of the European Commission (JRC), TP 261, I-21020 Ispra, Italy. E-mail: carlo.lavalle@jrc.it

Wolfgang Loibl, Austrian Research Centers - ARC Systems Research GmbH, Donau-City-Strasse 1, 1200 Vienna, Austria. E-mail: wolfgang.loibl@arcs.ac.at

Willem Loonen, Netherlands Environmental Assessment Agency (MNP), PO Box 303, 3720 AH Bilthoven, The Netherlands. E-mail: willem.loonen@mnp.nl

Pedro Lourenço, Departmento de Ciências e Engenharia do Ambiente, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Campus do Monte de Caparica, 2829-516 Caparica, Portugal. E-mail: pmbl@fct.unl.pt

Subrata K. Mandal, National Institute of Public Finance and Policy, 18/2 Satsang Vihar Rd. Special Institutional Area, 110067 New Delhi, India. E-mail: Subrata@nipfp.org.in

Maarten van der Meulen, Research Institute for Knowledge Systems (RIKS), PO Box 463, 6200 AL Maastricht, The Netherlands. E-mail: maarten@riks.nl

João Pedro Nunes, Departamento Ciências e Engenharia do Ambiente, Faculdade Ciências e Tecnologia, Universidade Nova de Lisboa, Campus do Monte de Caparica, 2829-516 Caparica, Portugal. E-mail: jpcn@fct.unl.pt

Koen P. Overmars, Department of Environmental Sciences, Wageningen University, PO Box 47, 6700 AA Wageningen, the Netherlands. E-mail: koen.overmars@wur.nl

Juan Peña, Departamento de Ecología, Universidad de Alicante, Ap. Correos 99, 03080 Alicante, Spain. E-mail: jpl@ua.es

Massimiliano Petri, Department of Civil Engineering, University of Pisa, Via Diotisalvi 2, 56126 Pisa, Italy. E-mail: m.petri@ing.unipi.it

Kampanart Piyathamrongchai, Centre for Advanced Spatial Analysis (CASA), University College London, 1-19 Torrington Place, London WC1E 6BT, United Kingdom. E-mail: ucfakpi@ucl.ac.uk

Eike Rommelfanger, Institute of Biometry and Population Genetics, Justus Liebig University, Heinrich-Buff-Ring 26-32, D-35390 Gießen, Germany. E-mail: eike.f.rommelfanger@agrar.uni-giessen.de

Mark Rounsevell, Départment of Géographie, Université Catholique de Louvain, Place L. Pasteur 3, B-1348 Louvain-la-Neuve, Belgium. E-mail: rounsevell@geog.ucl.ac.be

Juan Rafael Sánchez, Departamento de Ecología, Universidad de Alicante, Ap. Correos 99, 03080 Alicante, Spain. E-mail: jr.sanchez@ua.es

Henk J. Scholten, Department of Spatial Economics/SPINlab, Vrije Universiteit, De Boelelaan 1105, 1081 HV, Amsterdam, The Netherlands. E-mail: hscholten@feweb.vu.nl

Jan Ole Schroers, Institute of Agricultural and Food Systems Management, Justus Liebig University, Senckenbergstrasse 3, D-35390 Gießen, Germany. E-mail: jan.o.schroers@agrar.uni-giessen.de

Júlia Seixas, Departmento de Ciências e Engenharia do Ambiente, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Campus do Monte de Caparica, 2829-516 Caparica, Portugal. E-mail: mjs@fct.unl.pt

Ralf Seppelt, Department of Applied Landscape Ecology, Centre for Environmental Research (UFZ), Permoserstrasse 15, D-04318 Leipzig, Germany. E-mail: ralf.seppelt@ufz.de

Patrick Sheridan, Institute of Agricultural and Food Systems Management, Justus Liebig University, Senckenbergstrasse 3, D-35390 Gießen, Germany. E-mail: patrick.sheridan@agrar.uni-giessen.de

Maxim Shoshany, Department of Transportation and Geoinformation Engineering, Faculty of Civil and Environmental Engineering, Technion Israel Institute of Technology, 32000 Haifa, Israel. E-mail: maximsh@techunix.technion.ac.il

Michael Sonis, Department of Geography, Bar-Ilan University, 52900 Ramat-Gan, Israel. E-mail: sonism@mail.biu.ac.il

Klaus Steinnocher, Austrian Research Centers - ARC Systems Research GmbH, Donau-City-Strasse 1, 1200 Vienna, Austria. E-mail: klaus.steinnocher@arcs.ac.at

John Stillwell, School of Geography, University of Leeds, Leeds LS2 9JT, United Kingdom. E-mail: j.c.h.stillwell@leeds.ac.uk

Hanneke Tijbosch, Netherlands Environmental Assessment Agency (MNP), PO Box 303, 3720 AH Bilthoven, The Netherlands. E-mail: hanneke.tijbosch@falw.vu.nl

Harry Timmermans, Urban Planning Group/EIRASS, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands. E-mail: h.j.p.timmermans@bwk.tue.nl

Tanja Tötzer, Austrian Research Centers - ARC Systems Research GmbH, Donau-City-Strasse 1, 1200 Vienna, Austria. E-mail: tanja.toetzer@arcs.ac.at

Peter H. Verburg, Department of Environmental Sciences, Wageningen University, PO Box 47, 6700 AA Wageningen, The Netherlands. E-mail: peter.verburg@wur.nl

Roger White, Department of Geography, Memorial University of Newfoundland, St. John's, Newfoundland A1B 3X9, Canada. E-mail: roger@mun.ca

Zhi-Gang Wu, Center of Real Estate Research and Appraisal, Peking University, Rm. 3273, Bld. Yifuerlou, 100871 Beijing, China. E-mail: wuzhigang@pku.edu.cn

Su-Hong Zhou, Center for Urban and Regional Studies, School of Geography and Planning, Zhongshan University, 510275 Guangzhou (Canton), China. E-mail: eeszsh@zsu.edu.cn

Preface

The transformation of land use and land cover is driven by a range of different factors and mechanisms. Climate, technology and economics are key determinants of land-use change at different spatial and temporal scales. Whilst the implications of climatic warming at a global level are hugely worrying for low lying parts of the world, the processes of urbanisation continue in a seemingly uninterrupted manner. As time goes by, the use of land in both natural and man-made environments is influenced by the pressures associated with development. The demand for land for new residential housing in northwest European countries has been a huge challenge for governments striving to protect greenfield sites in recent years, whilst brownfield regeneration has been a common response to the decline of staple manufacturing in older industrial heartlands. The variety of forces that drive change in the use of land is extensive and complex, including spatial planning policies designed at local, regional, national and supra-national levels.

Given this complexity and in order to understand the mechanisms of change and the impact of policies, researchers and practitioners have turned their attention to formulating, calibrating and testing models that simulate land-use dynamics. These land-use change models help us to understand the characteristics and interdependencies of the components that constitute spatial systems. Moreover, when utilized in a predictive capacity, they provide valuable insights into possible land-use configurations in the future. Models of land-use change incorporate concepts and knowledge from a wide range of disciplines. Geography, as a spatial science, contributes significantly to the understanding of land-use change whilst demography and economics help explain underlying trends. Model building relies heavily on mathematics and (geographical) information science, but also includes many elements from the softer sciences, such as management studies and environmental science.

This book offers a cross-sectional overview of current research progress in the field of land-use modelling. The contributions that are included in the chapters of the book range from methodology and model calibration to the actual application of systems and studies of recent policy implementation and evaluation. The contributors originate from academic and applied research institutes around the world and thus offer an international mix of theoretical and practical perspectives in different case study contexts. The book is an indispensable guide for researchers and practitioners interested in state-of-the-art land-use modelling, its background and its application. A special website (www.lumos.info/ModellingLand-UseChange/Exercises.htm) provides demonstration versions of well-known land-use models that give detailed insights into the way these models work. Additional exercises and assignments help students to critically assess the potential of these instruments.

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Chapter 1

MODELLING LAND-USE CHANGE

Theories and methods

E. Koomen[1] and J. Stillwell[2]

[1]*Department of Spatial Economics/SPINlab, Vrije Universiteit Amsterdam, The Netherlands;*
[2]*School of Geography, University of Leeds, UK*

Abstract: This first chapter explains some of the basic theoretical ideas, concepts and methodologies that underpin the modelling of land-use change. It represents an overview of the types of approaches that have been adopted by researchers hitherto. It also provides a rationale for the structure of the book and a synopsis of the contents that follow.

Key words: Land-use change modelling; theory; methodology; book structure.

1. INTRODUCTION

The existence of the well-known computer-game, *SIM-City*™ (http://simcity.ea.com/), has taken the modelling of land-use change beyond its original domain of researchers and policymakers. Simulating the complex interaction of natural and social systems has now come within reach of computer games enthusiasts, both young and old. However, the popularity of the products generated by the games industry has not stretched as far as the land-use models that have been developed by researchers and planning practitioners. Some commentators might suggest that, during the last decade, these systems have tended to remain relatively under-used 'black boxes', producing little more than nicely coloured maps. Perhaps the lack of attention to the development of useful applications in the field of land use is related to the extensive array of existing models, the different approaches they take, and the relative complexity of their underpinning theories and methods of application.

E. Koomen et al. (eds.), Modelling Land-Use Change, 1–21.

This book aims to address this paradox by providing an overview of recent land-use modelling efforts and by clarifying their background and application possibilities. It does so by presenting a wide range of approaches (both geographically and thematically) that analyse and explain past land-use changes and simulate possible future changes. As an initial introduction to the simulation of land-use change, we begin with a discussion of some of the basic characteristics of land-use change models and the theories and methods on which they are based. Thereafter the structure of the book is explained and a synopsis of its contents is given.

2. CHARACTERISING LAND-USE CHANGE MODELS

Land-use change is a complex, dynamic process that links together natural and human systems. It has direct impacts on soil, water and atmosphere (Meyer and Turner, 1994) and is thus directly related to many environmental issues of global importance. The large-scale deforestations and subsequent transformations of agricultural land in the tropics are examples of land-use change with strong likely impacts on biodiversity, soil degradation and the earth's ability to support human needs (Lambin *et al.*, 2003). Land-use change is also one of the important factors in the climate change cycle and the relationship between the two is interdependent; changes in land use may affect the climate whilst climatic change will also influence future land-use (Dale, 1997; Watson *et al.*, 2000). On a smaller scale, in the densely populated parts of the urbanised western world, land-use change is the expression of continuing urbanisation pressure on ever scarcer open spaces (e.g. Bell and Irwin, 2002; Rietveld and Wagtendonk, 2004), many of which have been designated by planning authorities as greenfield areas for conservation reasons. This issue is often referred to as urban sprawl, a topic of debate in the United States especially (e.g. Brueckner, 2000; Glaeser and Kahn, 2004). Modelling land-use change helps understand the processes of continuing urbanisation and can also be of value in informing policymakers of possible future conditions under different scenarios. Land-use change models can therefore be defined as tools to support the analysis of the causes and consequences of land-use change (Verburg *et al.*, 2004a). Many authors (e.g. Lambin *et al.*, 2001) make a distinction between the *land cover* that can be observed (e.g. grass, building) and the *land use,* the actual use to which the land is put (e.g. grassland for livestock grazing, residential area). For convenience, we use the term land use predominantly in this book, referring to both land cover and actual land use.

Recent inventories of operational models for land-use change are numerous. Briassoulis (2000) offers a very extensive discussion of the most common land-use change models and their theoretical backgrounds. Waddell and Ulfarsson (2003) and Verburg *et al.* (2004a) present more concise overviews that focus on the future directions of research in this field, whilst more detailed, technical information on the actual models is provided by Agarwal *et al.* (2002) and the U.S. Environmental Protection Agency (U.S. EPA, 2000). All inventories show a very heterogeneous group of instruments with considerable differences regarding their background, starting points, range of applications *et cetera*. We will refrain here from classifying existing models, but rather discuss a number of characteristics that can be used to differentiate the most common modelling approaches.

One of the most important distinctions refers to *static* as opposed to *dynamic* models. Static (or cross-sectional) models directly calculate the situation at a given point in time, whereas dynamic models work with intermediate time-steps, each of which might become the starting-point for calculating the subsequent situation. Dynamic modelling, therefore, takes possible developments during the simulation period into account, providing a richer behaviour and the possibility to better mimic actual spatial developments.

Land-use change models can also be characterised as dealing with either *transformation* or *allocation*. Transformation models start from the current land use and simulate the possible conversion into another land-use type, e.g. based on a transformation probability or the status of surrounding locations. Allocation models, on the other hand, allocate a certain type of land use to a location based on its characteristics. Current land use may thus be one of the factors influencing locational characteristics, but it is not necessarily preserved in future land use. This approach to simulation basically starts with an empty map.

From a theoretical perspective, there is a clear difference between models starting from a direct emphasis on *land use* and those whose initial consideration is the *land user*. Many models focus purely on land use, merely simulating its state at a certain location. Other approaches take land users as the starting point and try to understand their behaviour. The description of the spatial decisions of (groups of) individuals is then used to deduce the land-use changes.

Approaches to simulating land-use change may be either *deterministic* or *probabilistic*. The former applies strict cause-effect relations, whereas the latter considers the probability of land-use changes taking place. The essence of this second approach is the introduction of an element of uncertainty. A type of use is attached to a location based on an estimated probability, rather than following a straightforward deductive approach. In some cases, a random error-term is added to express the uncertainty in the explanatory factors.

Another common distinction is the one made between *sector-specific* and *integrated* models. Sector-specific models focus on one part of the land-use system (e.g. housing, employment, agriculture) and describe that part as precisely as possible. Integrated models consider the mutual relationships between these sectors, thus approaching the land-use system in a very comprehensive and inter-dependent (or systems-oriented) manner. Truly integrated models also incorporate the feedbacks of the land-use system with other related systems such as climate, hydrology or transport.

In relation to the spatial level of detail, both *zones* and *grids* are used. Zones are relatively homogeneous, often irregularly shaped areas or vector polygons, e.g. socio-economic or administrative regions that more often than not have little functional coherence. Grids, on the other hand, are collections of (mostly square) cells defined in a regular raster pattern that are often used in geographical information systems (GIS). Models that use grids often make use of geographical information from other sources, thus having access to valuable base data.

As land-use change models can differ from each other on all of the above mentioned characteristics, classifying them into homogenous groups is difficult, if not impossible. They do rely, however, on a limited number of basic principles to allocate land use and these theories are discussed in the next section.

3. THEORIES AND METHODS OF LAND-USE MODELLING

Models for simulating future land use exist in many different types and forms, but they all rely on a limited number of theories and methods. Economic theories, for example, are often used to explain land-use patterns and their dynamics (e.g. Bockstael and Irwin, 2000; Irwin and Geoghegan, 2001). The underlying idea is that those who can afford the most money for the land are the ones using it. But disciplines such as geography and mathematics have also contributed to the understanding and simulation of changes in land use. In order to provide some background for the models that will be presented in later chapters of the book, we introduce some of the basic principles of land-use modelling. For an introduction to a number of additional aspects that are relevant for the simulation of land-use change, such as policy perspectives, driving forces, data considerations, evaluation and visualisation methods, the reader is referred to a previous text, *Land Use Simulation for Europe* (Stillwell and Scholten, 2001).

3.1 Economic principles

For a number of reasons, land is a special economic asset. Firstly, the supply of land is fixed, creating specific demand-supply relations. Secondly, every parcel of land has a fixed location with its associated unique features in terms of soil quality, gradient, altitude, accessibility *et cetera*. The marketable asset is therefore far from homogeneous, severely hampering the price-making analysis. Thirdly, the land use at a certain location influences its surroundings. The impact may be either negative or positive; basic infrastructure or industry causes visual disturbance for many, but small-scale agriculture may increase the aesthetic or natural value of the landscape. This impact, that economists call an externality of land use, often gives rise to government intervention. Examples of this intervention include prohibition of dwellings in the proximity of big industrial estates or airports, economic activities that are relocated to the outskirts of cities, or farmers that receive subsidies to provide 'nature' as an additional product under sub-optimal agrarian conditions. Combined with the limited supply and the heterogeneity of land, the externalities and the resulting government interventions are expressed in a segmented land market, where different prices are used for 'green' (agriculture, nature) and 'red' (housing, employment, infrastructure) functions and where considerable spatial price differences exist within sector-specific markets (e.g. Buurman *et al.*, 2001).

The focus on land in economic theories has changed over time. The early and well-known theories of Ricardo and, in a more spatial context, Von Thünen, have laid the foundation of land-price and land-use theories. These are to a certain extent still valid and used in current research. Ricardo (1817, in Kruijt *et al.*, 1990) explained land prices in terms of differences in soil fertility levels or, more generally speaking, in terms of land quality. Better quality land is more profitable than lower quality land, and this difference leads to payment of a higher price for the land. Von Thünen (1826) focused on the impact of distance and hence transportation costs, to explain land-use patterns and land prices. Current economic analysis of land use often takes bid rent theory (Alonso, 1964) as a starting point, focusing on the relationship between urban land use and the value of urban land. Individual households and companies weigh up the land price, transportation costs and the amount of land they need. This leads to a simple model with decreasing land prices as you move away from the city centre. The land use resulting from these assumptions is that of a typical monocentric city. Commercial activities are concentrated in the city centre (central business district); industrial and housing functions will have less money available for a central location and will select a location at a greater distance from the centre; the edge of the city is identified where the offer of the urban bidders is equal to that of the agrarian bidders.

Another important concept related to economic science and used to explain land-use patterns is discrete choice theory. Nobel prize winner McFadden has made important contributions to this approach of modelling choices between mutually exclusive alternatives (e.g. 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 the *suitability* for a certain use. This can be formulated as follows:

$$X_{ci} = e^{\beta * S_{ci}} / \sum_{k} e^{\beta * S_{ck}} \qquad (1)$$

where:
X_{ci} is the probability of cell *c* being used for land-use type *i*;
e is the base of the natural logarithm (= 2.71828);
S_{ci} is the suitability of cell *c* for land-use type *i*; dependent on different factors;
S_{ck} is the suitability of cell *c* for all (*k*) land-use types; and
β is a parameter to adjust the sensitivity of the model.

The suitability of a location for a certain use can be explained by a range of different factors. This may refer, for example, to physical suitability, as is the case with the soil type that largely determines the most profitable type of agricultural use. Other important aspects that influence suitability include accessibility of relevant facilities or spatial policies that will restrict or encourage certain land-use types. 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.

The renewed interest for geography in economics (e.g. Krugman, 1999) offers interesting concepts to analyse the spatial interaction between actors (represented by, for example, residences or industries) in terms of centripetal forces leading to concentration, and centrifugal forces leading to a spatial spread of functions.

3.2 Spatial interaction

A classical group of land-use models is based on spatial interaction modelling theory. Spatial interaction in a social, geographical context refers to every movement in space as a consequence of a human process (Haynes and Fotheringham, 1984). By analogy with Newton's first law, these models assume that the interaction between two entities depends on their own mass (or size) and is inversely proportionate to the distance between them. Early applications of this principle can be found in studies of migration (Ravenstein, 1885; Young, 1924) and trade (Reilly, 1931). Their main assumption was that the volume of interaction, being migration or commercial transactions between two cities, for example, depended on the size of the two cities and the distance between them. Thus, bigger cities were expected to attract more migrants or trade than smaller ones and this flow of migrants or trade was expected to be strong when distances were small.

This way, the concepts of scale and distance are introduced in the description of spatial relations, indicating that their influence is relative; size matters, especially when distances are small. This simple gravity principle has been adjusted and extended in several different ways. An important extension is the inclusion of more than two objects. The total interaction in a system is supposed to be equal to the sum of all interactions between all pairs of objects or, in other words, the interaction potential of an object is equal to the sum of all potential interactions with other objects.

Lowry (1964) was the first to develop an urban land-use model based on two dependent gravity models. The first model relates the population distribution to residential areas on the basis of fixed employment locations. The demand for trade can then be deducted from the population distribution. The second gravity model allocates retail businesses based on the newly determined demand. The changed distribution of services results in an adapted demand for labour force that can be introduced in turn in the population model. This dynamic interaction will continue until a previously defined small amount of allocation difference occurs. The Lowry model is spatially explicit on the level of homogeneous urban zones. Current land-use models display a higher level of detail in both their spatial resolution and allocation principle, but often fall back on this type of model for the sector-specific demand for land.

The primary architect of contemporary spatial interaction modelling is Alan Wilson, whose seminal work in the late 1960s (Wilson, 1967) on entropy maximisation led to the inclusion of balancing factors in the gravity model equations that served to ensure constraints were satisfied. A family of models was developed (Wilson, 1970), variants of which could be applied in situations of differing known information. In the context of migration, spatial interaction models based on these principles have been extended by Stillwell (1991) and Fotheringham (1991) and used recently in an applied context to model flows within the UK for the Office of the Deputy Prime Minister (Champion *et al.*, 2003).

A related type of research focuses on the interaction between land use and transport. Central to this approach is the assumption that land use is influenced by the available infrastructure network and *vice versa*: the transportation demand depends on the spatial configuration of the different, mostly urban, land-use types. One of the first researchers to model the interdependence of these systems was Putman (1983), but many others have created similar structures, often referred to as LUTI models, more detailed overviews of which are provided in Wegener (1998) and Kanaroglou and Scott (2002), for example. Most of the original LUTI models were based on a classic spatial interaction framework and adopted a relatively coarse zonal scale. In the newest wave of these models, however, research attention has shifted towards activity-based microsimulation (Timmermans, 2003). This is a trend that is also visible in general (non-transport related) land-use change models as will be discussed later.

3.3 Cellular automata

The cellular automata (CA) methods deriving from mathematics are very well suited for imitating complex spatial processes on the basis of simple decision rules (Wolfram, 1984). Every cell has a certain state (or function) that is influenced by its surrounding cells as well as the characteristics of the cell itself. The degree and direction of interaction between the functions is determined through so-called transition rules. The application of CA in geographical modelling was originally proposed by Tobler (1979) and the concept has subsequently been applied to model urban form (Batty, 1997; Yeh and Li, 2001), urban growth (Clarke *et al.*, 1997; Couclelis, 1997; Clarke and Gaydos, 1998), land-use planning (Wu, 1998; Li and Yeh, 2000) and urban and regional development and planning (Samat, 2002; Engelen *et al.*, 1999; White and Engelen, 2000).

A strong dimension of this approach is the simulation of the interaction of a location with its direct surroundings that has empirically proven to be an important driver of land-use change (O´Sullivan and Torrens, 2000; Verburg *et al.*, 2004b). A crucial component of this local interaction approach is ‘emergence’, discussed by Holland (1998) amongst others. In CA models this phenomenon refers to global patterns that appear spontaneously from the collective behaviour of individual cells influencing each other. This rich behaviour leads to simulation results that are very hard, if not impossible, to predict from the behaviour of the individual cells.

Additional, location-based information is often used in creating the transition rules in CA models, for example relating to the physical suitability or policy restrictions within a cell. The model thus moves beyond the classical focus on spatial interaction to achieve more realistic simulations. Classical CA models have a limited theoretical relationship with the decision-making process that leads to changes in land use. Hence, modern CA applications also incorporate components from other disciplines to obtain a more realistic simulation of land-use changes, an example of which is the Markov model that uses transition probabilities to describe the possible spatial developments of a location (Balzter *et al.*, 1998; Li and Reynolds, 1997). The probability of a cell changing its function is determined here by the initial state of the cell, the surrounding cells and a transition matrix with its transition probabilities. The interesting aspect of this approach is that consecutive changes in land use known from the literature or from experience (e.g. a succession in vegetation types or the changeover from agricultural to residential use) can be included explicitly as being probable whereas other transitions (e.g. industry to agriculture) can be described as being improbable or, in some cases, impossible. The cell changes its status according to these estimated probabilities rather than from the deterministic transition rules of the classical CA models.

Another option to control the spatial interaction behaviour of individual cells in CA models is the inclusion of higher level constraints on, for example, the magnitude of land-use changes. This can be implemented through a regional level spatial interaction model as is the case in the *Environment Explorer* model (White and Engelen, 2000) and related *MOLAND* framework (Engelen *et al.*, this book).

3.4 Statistical analysis

Statistical analysis is an essential tool for almost all models of land-use change. Regression analysis, for example, helps to quantify the contribution of the individual forces that drive land-use change, as demonstrated by Rietveld and Wagtendonk (2004) and Verburg *et al.* (2004c) and thus provides the information needed to properly calibrate models of land-use change. An important aspect of analysing land-use patterns is addressed in spatial econometrics and relates to issues such as spatial dependency and spatial heterogeneity (Irwin and Geoghegan, 2001). The analysis of spatial dependence may point to structural interdependencies between, for example, land-use types and can be useful in formulating the transition rules in CA-models. See Anselin and Florax (1995) for an extensive discussion of this topic.

Many examples exist of models that rely solely on a statistical description of observed past land-use changes to simulate future patterns (e.g. Schneider and Pontius, 2001; Serneels and Lambin, 2001). These empirical-statistical models have the advantage of being relatively easy to construct, but they miss a theoretical foundation as no attempt is made to understand and simulate the processes that actually drive land-use change. The applicability of these purely statistical models is therefore limited. They can be used to simulate possible spatial developments within a relatively short time-span under 'business as usual' conditions, but they are not suited to simulate possible changes according to diverging socio-economic future scenarios, for example. A combination with theoretical insights in land-use change processes is therefore welcomed to add a notion of causality to statistical models (Veldkamp and Lambin, 2001; Parker *et al.*, 2003). Examples of this combination are provided by Chomitz and Gray (1996) and Geoghegan *et al.* (2004).

3.5 Optimisation techniques

Another modelling approach is optimisation. By applying mathematical optimisation techniques such as linear integer programming or neural networks, the optimal land-use configuration is calculated here given a set of prior conditions, criteria and decision variables (e.g. Aerts, 2002; Pijanowski *et al.*, 2002). The simplest applications aim to optimise a single objective (for example, profit maximisation) for a specific group of decisionmakers (e.g. project developers). But there are also mathematic programming techniques that can determine the optimal solution for different, divergent objectives. This is especially interesting for policymakers who are interested in the optimal configuration of an area based on different, often conflicting, policy goals. This approach is further discussed in Part III of this book.

3.6 Rule-based simulation

The central element in rule-based simulation is the imitation of a known process. This approach is generally used in the field of physical sciences and is often applied in combination with a GIS. Rule-based simulation models can be used to imitate processes that can be described by strict, quantitative, location-based rules. These are normally natural processes such as soil erosion or landscape dynamics. The latter is modelled, for example, in the Landscape Modelling Shell (*LAMOS*, see Lavorel *et al.*, 2000) that integrates a quantitative description of different landscape processes, such as vegetation succession, disturbance and dispersal, to simulate possible landscape-ecological patterns.

The rule-based approach has also been applied, however, in studies with a more socio-scientific orientation such as land-use change. Examples of the application of rule-based simulation models include the original California Urban Futures (*CUF*) model and the *What If?* system. A typical feature of these models is that they allow users to include explicit decision rules that steer their behaviour (Klosterman and Petit, 2005). This flexible characteristic allows the models to simulate the consequences of spatial decisions and thus makes them useful as planning support tools. *CUF* (Landis, 1994) simulates alternative residential-development scenarios for cities based on specified policy changes at various levels of government. Projected population growth based on past trends is allocated and the profitability of each land parcel if developed is ascertained based on this demand, but also on user-specified development regulations and incentives. *What If?* (Klosterman, 1999) is a self-contained visualisation tool that accepts user-defined spatial data, growth rules and parameters to map land-use allocation alternatives.

Rule-based simulation is also an important element in many integrated models of global change as described by Alcamo *et al.* (1998) and Cramer *et al.* (2001), for example. These models typically apply relatively simple descriptions of the relations between various subsystems to simulate their interaction and assess the resulting state of, for example, land use, vegetation cover or greenhouse gas concentrations. The subsystems (e.g. economy, emissions, vegetation, agriculture and atmosphere) are often modelled in more elaborate, individual models.

3.7 Multi-agent models

Human decision making and interaction are the central elements in multi-agent (MA) models. The key concept here is that of the agents or decisionmakers. Parker *et al.* (2003) define agents as being autonomous, yet sharing an environment through communication and interaction, and they take decisions linking their behaviour to their environment. Autonomy means that the actors control their own actions and internal status in order to achieve their goals.

In MA models, as a minimum, actors have a strategy that makes them react to their environment and the actions of other actors. More advanced models of human decision making apply the rational choice theory. These models assume agents being fully informed, taking long-term decisions and having infinite analytical capacities. It is very difficult, however, to combine these models with the decision-making processes related to land-use change. It remains to be seen whether those complex decision-making models can be used to simulate land-use changes. Because of different spatial dependencies and feedback mechanisms, it is virtually impossible for an individual actor to consider all possible consequences of his own acts and those of all other actors. Hence, many MA models apply a type of limited rationality for the choice behaviour of their actors (Parker *et al.*, 2003). A recent overview by Berger and Parker (2002) on MA models for land-use changes shows different applications from the whole world on topics such as crop choices, deforestation and urbanisation. The choice behaviour therein is modelled with the assistance of relatively simple rules of thumb (heuristics), limited rationality or (economic) utility functions. MA models appear mainly effective in combination with CA models. The CA part then describes the natural system (the interaction between ecological processes and the physical subsoil), while the MA part describes the human part (choice behaviour of actors). The potential of CA and MA models currently under development in academic institutions to act as planning support systems with practical application in the real world has been reviewed by Torrens (2003). Several examples of this approach are described in Part IV of this book.

3.8 Microsimulation

Microsimulation is related to the simulation of processes at the level of individuals. Within land-use models, the idea is to include all individual actors who influence changes in land use. In this sense, this approach deviates from the multi-actor approach that uses a cross-sectional (average) description of the relevant decision-making groups. An important advantage of this method is that land-use changes are modelled on the scale level on which the actual choices are also made. Microsimulation demands enormous amounts of data and therefore computing power to simulate the actions of all relevant individuals. But as more detailed spatial data and faster computers become available, this approach is gaining popularity. For a description of the choice behaviour of individuals, one is often referred to (microeconomic) discrete choice theory, such as is used in the *UrbanSim* model (Waddell, 2002; Felsenstein *et al.* this book). The big challenge continues to be the reconciliation of microsimulation with the macro-scale socio-economic processes, such as structural economic and demographic developments (Alberti and Waddell, 2000).

3.9 Application of the theories and methods

All of the described theories and methods have their own advantages and disadvantages. The economic approach is useful to model choice behaviour in sector-specific submarkets, like the agricultural or urban land market. CA models on the other hand, are apt to model land-use changes when the interaction with the surroundings is important. This is the case, for example, when physical or ecological aspects are dominant as with deforestation. Optimisation models can be used to determine the optimal land-use configuration according to certain (policy) goals and are mostly applied to inform decision makers of possible solutions for land-use management issues.

Table 1-1 links this book's land-use change models with the theories and methods introduced in this section. Due to the complexity of most of the models, these links are not always straightforward and may even depend on the application that is described. The table merely indicates the prevalent theoretical and methodological background. The models that basically aim at explaining current and past land-use changes (Chapters 6, 7 and 8) offer a relatively straightforward approach, as do the land-use optimisation efforts described in the subsequent three chapters. None of the individual approaches can, however, provide a basis for a comprehensive, integrated and spatially explicit model to simulate future land-use change in a complex modern society. Such models therefore often combine different approaches into one hybrid model as was also advocated by Torrens (2001). The land-use simulation models presented in this book indeed rely on a combination of different theories and methods, as is discussed below.

The recently developed models that focus on the behaviour of agents in particular incorporate many theories and methods in their frameworks. The renowned *UrbanSim* model, discussed in Chapter 12, is an example of an interesting hybrid model that combines a microsimulation approach with discrete choice theory for the location choice of individual households and general economic theory for macro-economic evolution. Statistical analysis is used to actually quantify the behaviour of these agents. The new *PUMA* model (Chapter 14) also combines an agent-based approach with economic theory (utility-maximising functions) and statistical analysis to describe the choice behaviour of households.

Most of the other much applied integrated land-use simulation models also rely on a combination of theories and methods. The *LUMOS* toolbox (Chapter 16), for example, provides a framework for land-use simulation that, amongst others, contains the *Environment Explorer* and *Land Use Scanner* models. The former model is comparable to the *MOLAND* modelling framework (Chapter 17) and is essentially a CA model, but it is combined with a spatial interaction model to constrain regional land-use demand. Statistical analyses and expert judgement are furthermore used to estimate local transition potentials. The *Land Use Scanner* (Chapters 16 and 20) applies an allocation algorithm that is based on economic, discrete choice theory. The additional application of constraints on regional demand and the supply of land, however, enforce a bidding process that is in line with other economic (bid-rent) theory. This model also relies on expert judgement to define local suitability and prospected claims for the different land-use types following the specified scenario conditions, adding a rule-based element to the simulations. The *CLUE-s* model (Chapter 18) provides a framework for land-use simulation that, depending on the constructed configuration, can contain elements of statistics, cellular automata and a rule-based approach.

Table 1-1. Theoretical and methodological background and case study area of the land-use simulation models presented in this book

Model name or method (chapter number)	Economic principles	Spatial interaction	Cellular Automata	Statistical analysis	Optimisation	Rule-based	Multi-agent models	Microsimulation	Described case study area
Markov model (6)				X					Marina Baixa, Spain
Statistical analysis (7)				X					Southern Belgium
Spatial interaction (8)		X							Corvo island, Azores, Portugal
Genetic algorithm (9)					X				Netherlands
Linear programming (10)					X				Hawalbag, India
GeneticLand (11)					X				Southern Portugal
UrbanSim (12)	X			X			X	X	Tel Aviv region, Israel
Multi-agent simulation (13)				X			X	X	Rhine valley, Austria
PUMA (14)	X			X			X	X	Randstad, Netherlands
DSSM (15)		X	X	X					Chiang Mai, Thailand
LUMOS (16)	X	X	X		X				Netherlands
MOLAND (17)		X	X						Urban areas across Europe
CLUE-s (18)			X	X		X			Netherlands and Malaysia
SELES environment (19)				X		X			Leipzig-Grünau, Germany
Land Use Scanner (20)	X					X			Netherlands and Elbe area
ProLand and *UPAL* (21)	X					X			Hesse, Germany

Note that the first chapters of the book are not included in this table because they focus on the analysis of land-use change rather than its simulation.
LUMOS and *CLUE-s* provide frameworks for land-use simulation consisting of various models and configuration possibilities that each rely on different theoretical and methodological backgrounds.

4. STRUCTURE OF THE BOOK

This book presents a cross-sectional overview of recent research progress related to the modelling of land-use change. The contributions range from analysing past land-use changes to simulating future changes to help policymakers take their decisions. The case studies that are presented in the