Advances in geomatic simulations for environmental dynamics

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Abstract
Modelling environmental dynamics aids in the understanding and anticipation of future evolutions. Their prospective simulation supports decision-making for environmental management. This introductory chapter gives an overview about the context, objectives and opportunities (the challenges), followed by a summery of the methodological approaches commonly used in environmental modelling and simulation. Based on this general opening, the third part presents comprises chapters, which are case studies applying various models to a large array of themes: deforestation in tropical regions, fire risk, natural reforestation in European mountains, agriculture, biodiversity, urbanism, and land management. In this section, authors provide a comparison of these case studies based on several criteria such as objectives, scales, data, study areas, calibration and validation techniques, results and outcome.

Keywords: Modelling, spatio-temporal dynamics, environment, validation, geomatics.

1.1 Challenge

1.1.1 Context

The modelling of environmental dynamics means the simulation of the behaviour of an environmental system in space and through time. This research challenge has many aspects such as a better comprehension of complex environmental processes or decision support for environmental management and land planning. Anticipating 'what would happen if' has become a routine question in many research domains such as risk prevention, environmental impact studies, etc. Geomatics, and especially Geographical Information Systems (GIS), deal with spatio-temporal data. At first GIS was only able to process spatial queries such as the overlaying of different layers or attribute queries based on relational data bases. During the last few decades, these traditional GIS functions were enhanced with new components including a temporal dimension. Today various GIS software offers either generic or objective specific modelling tools of interest for geography and environmental sciences, which are able to assist in research challenges such as global climate change or land use/land cover dynamics. While classical GIS achieves only one step in order to resolve actual problems in land planning and environmental management, and must be connected to one or several specific software, the latest generation of geomatic tools, such as GIS, offers integrative and flexible toolboxes.

Geocomputation (Atkinson and Martin 2000, Openshaw and Abrahart 2000) is a new term referring to this new group of more complex techniques in GIS that includes computer techniques such as artificial neural networks, fuzzy logic or genetic programming. Brimicombe (2003) talks about a new paradigm (the geocomputational paradigm) combining GIS, simulation modelling and engineering.

Buzai (2006) points out that geocomputation, together with geographical information science and integrated social sciences form the three new fields in geography. Following Buzai, geocompution, also called ‘advanced methods’, creates spatial results, but the principal data processing functions, performing alternative solutions and scenarios have an undoubtedly decisional character.

As geocomputation stresses computer science, we prefer to talk about geomatics, a word that first appeared in French-speaking Canada, particularly at the University of Laval during the 1980’s. The term geomatics, including all forms of spatial data processing, is rather midway between geography and computer sciences. Laurini and Thompson (1992) made one of the first definitions about geomatics. Presently it’s an important line of research in geography and environmental sciences. If spatio-temporal models can be used with two objectives – description and explanation of dynamics and their simulation or possible scenarios – we focus on the latter: simulation models offering geomatic solutions, that is to say geomatic simulations.

Simulations can be created for current situations in order to compare them with real maps but also to anticipate future changes. Different scenarios correspond to divergent evolutions and can offer important keys for planners and policy measures. Applying and comparing models and validating and evaluating results, offer a rich source of knowledge both in thematic and in methodological research. A bibliographic overview of recent research in environmental modelling confers an optimistic image of the accomplished advances. However, as recently as the 1990’s the situation wasn’t as optimistic. Le Berre and Brocard (1997) noticed that GIS capabilities were widely under-employed and that the majority of modelling research in geography was rather static and done simply to resolve spatial distribution problems. They explain the lack of dynamic models and spatio-temporal simulations by the precedence of static models such as urban models (city types, centrality, and attractivity).

Langlois and Philipps (1997), according to the origins of modern modelling, emphasize the relation between technological innovation and paradigm change. They illustrate this with an example: the important role of factor analysis in the change from a mechanical to a multi-dimensional view of the world. Based on the research of Spearman (1904), only a few researchers employed this statistical method before the availability of computers at the end of the 1950's. The change in the paradigm to a dynamic and systemic approach in understanding and analyzing complex ecosystems and geosystems was driven by numerous advances (e.g., ecological deterministic models, quantitative geography, expansion of computer sciences, etc.).

During the last two decades the methodological approaches for modelling were profoundly enhanced or, at least, popular in human and social sciences. Classical stochasticity became complemented by artificial intelligence based approaches, like neural networks and multi agent systems, but also by techniques like cellular automaton and fuzzy logic. Today researchers have at their disposal a wide range of modelling concepts and methods. Nevertheless, a lot of work has to be done to improve, validate and generalize models for spatio-temporal simulation of complex environmental dynamics, in order to create standard tools, which can be used by non-specialists. Consequently, the actual context may be described as 'how to transform advances in research into operational tools.' Thus trying to satisfy an increasing social demand for decision support for environmental management, sustainable development, and risk prevention from the local level to a global scale.

1.1.2 Objectives

Bregt et al. (2002) describe a three step approach in order to classify models dealing with spatial and temporal data. These authors distinguish between an initial state (the *What is where* question), which requires only spatial data to be exploited by classical models in GIS, and a second state (the *What is changing where?* question). To answer this second question, the database must also include temporal data like time intervals, in order to understand the process of change and the interaction between factors by the use of models for space-time data. For the third question (*What will be where?*), these models call on not only on explanations of past dynamics, but also on time projections such as prospective prediction or scenarios. Accordingly the standard database and GIS functions must be complemented by some additional, modelling specific, software components.

With these three questions we intend to describe the principal terms that describe the content of this book.

- *What?* First, it's necessary to understand what our objective theme is. We define environmental dynamics in a broad sense, including natural risks, forest or agricultural dynamics and urban growth. Several chapters focus on land cover/land use change at a regional or local scale.
- *With what?* What are the tools we can use? A spatio-temporal database must be built and exploited and its elaboration is one of the most delicate and decisive operations for the correct use of the models. Among the different models used for environmental dynamics, we choose preferentially geomatic solutions calling on GIS, remote sensing and other specific tools.
- *For what?* What is the outcome of these procedures? Chronologically, perhaps it's possible to see an evolution from the more classical analysis and description of outcomes in the spatio-temporal database exploitation to the more recent models. Scientists have procured explanations from the phenomena, before trying to model them.

But, modelling for what? Earlier, we referred to the two principal objectives of spatio-temporal models: explanation/description of the dynamics, and simulation/projection of them. Also Skidmore (2002) states that an environmental model seeks to understand or explain environmental systems, but also can be used to predict future scenarios or to compare the predictions with reality. They remark that "However, a model should not be used for both prediction and explanation tasks simultaneously…"

In this book, we focus primarily on modelling for predictive simulation and time projection. Regardless, some simulations have tried to explain particular dynamics, and to analyse past and present environmental processes.

What? **OBJECT**	***With what?*** **TOOLS**	***For what?*** **OUTCOME**
Environmental dynamics	**Geomatics**	
		Spatio-temporal database
		Analysis – Description
		Modelling for explanation
		Modelling for simulation

Fig. 1.1 Basic questions in modelling

The following pages intend to study thoroughly these three, above-mentioned questions (Fig 1.1). In spite of focussing on the content of the present book, these paragraphs are also relevant to this research area in general.

1.1.2.1 What? (Object): Environmental dynamics

When discussing the object of modelling environmental dynamics, temporal and spatial scales must be considered. If we begin with *time,* there are several approaches: dynamics can be progressive or regressive, slow or fast; time account into the model can be short, middle or long. Time can be continuous or split into discrete time steps and the model can run in real time or not. Temporal resolution also depends on databases or modelling methods (some models need more dates to work correctly than others). Finally, environmental modelling occurs more frequently as a prospective simulation. Retrospective modelling or historic simulation is rarely undertaken with geomatic solutions (See Chap. 9).

Time scale is linked to the *spatial* scale. Scale in GIS is often "…handled poorly in such systems…" (Tate and Atkinson 2001). Like time, spatial scales are affected by diversity and overlapping: global, middle or local spatial scales are, all of them, the objects for modelling as any quick bibliographical query can attest to. One can find studies from the local scale (small areas with fine spatial resolution) through regional scales to the continental and even at the global level (large areas with small spatial resolution). Many of the more recent works in environmental modelling focus on thematics encompassing vast areas, from the continental to the global scale (as examples: 140 million cells at 1 km² performed to analyse land use changes in the whole Amazonian basin by Soares Filho et al. 2006, the continental-scale urban modelling approach of Reginster et al. 2006). In any case, local and regional scales continue to be the common preference for geomatic based model implementation.

A comparison between these application scales can lead to several conclusions, such as that all of them have advantages and disadvantages and that models built for small or larger areas often can not be adapted to a different scale. This fact can be explained by numerous considerations (see Sect. 14.4). On the one hand, the number of land use categories and the sense of the nomenclature depend on scale. On the other hand, a lot of thematics need spatial accuracy or deal with scale-dependent phenomena such as spatial patterns (e.g., road-influenced, radial or diffuse growth). Also some thematics are dependent on data that are only available at one-scale.

Consequently, time and spatial scales are linked, and they are also linked to the *thematic objective*. A complete overview about specific fields of interest for environmental modelling with GIS was undertaken by Goodchild et al. (1993, 1996), bringing together more than a hundred contributions and showing all the variety of thematics.

Recently, we have raised awareness and concern about global changes, including efforts for modelling them. Monitoring the deforestation, ozone layer depletion, food early warning systems, monitoring of large atmospheric-oceanic anomalies, climate and weather prediction, ocean mapping and monitoring, wetland degradation, vegetation mapping, soil mapping, natural disaster and hazard assessment and mapping, and land cover maps for input to global climate models are some of the most important objectives of this research branch in environmental modelling at the global scale (Skidmore 2002).

In Wainwright and Mulligan (2004), environmental modelling is prominent in many disciplines such as climate, soil, hydrology, fluvial processes, ecosystem, biogeochemical modelling, among others. Another example is the forest landscape change models, which also use longer temporal series, related to some topics familiar to global change research such as sustainability, ecosystem management, and biodiversity protection (Mladenoff and Baker 1999).

We just mentioned some references offering an exhaustive overview about the thematics belonging to or overlapping environmental dynamics. Repeating this is not the objective here. Thus we only want to stress some of the 'most popular' themes with the aim to emphasize the social utility and the urgency to contribute to resolving these problems: natural disaster and natural and technological risks, climate change, wildlife modelling, ecological and landscape modelling, deforestation, LUCC (land use/land cover change) often related to land planning, food watch and urban growth.

1.1.2.2 With what? (Tools): Geomatics solutions

We note a chronological evolution in geomatics from spatio-temporal analysis toward spatio-temporal modelling. Spatial data at time intervals (a spatio-temporal database) is our principal source and we have found a great number of contributions in which the terms "time – space – modelling – geomatics" are used in the last decades.

Geomatics integrate all the techniques of geographical information systems (GIS), remote sensing (RS) and other disciplines, methods and tools deal with spatial data. It's important to remember the known complementarities between GIS and remote sensing, particularly in modelling because spatial components are linked to temporal components in an integrated tool. Both GIS and RS often work together, remote sensing offering regular temporal databases for monitoring environmental dynamics.

But we must remember that modelling in geomatics has been traditionally developed in spatial analysis. *Spatial modelling* with GIS and other tools is a very important line of research. As a part of what often is called 'geostatistics' (Burrough and McDonnell 1998) or 'geospatial analysis' (Longley et al. 2007), research in spatial models sometimes emphasizes the integration of different spatial analysis functions with a focus on problem solving in practical cases (Longley and Batty 1996, 2003, for urban planning, transportation, and economic development; Stillwell and Clarke 2004, for geo-business, transport or spatial planning) or for policy evaluation (Fischer and Nijkamp 1993).

Other more methodological works show the new potential and innovative modelling approaches in spatial models and GIS (Fotheringham and Wegener 2000) and the complementarities between geostatistics and the machine-learning algorithms (Kanevski and Maignan 2004). In some cases, modelling of spatial data focuses only on one type of model, like the fuzzy process (Petry et al. 2005) or on a specific thematic objective, like geological sciences applied to mineral exploration (Bonham-Carter 2002).

However the irruption of the *temporal factor* in geomatics, which began about two decades ago (Langran 1992, 1993, Egenhofer and Golledge 1994), has turned the concept of *time* into one of the more important components in new technologies. Previously mentioned authors and other researchers (e.g., Cheylon et al. 1994, Lardon et al. 1997) deserve the merit for the implementation of time into GIS, since then it has been called temporal GIS (TGIS) (Christakos et al. 2001). Theoretical thought and methodological aspects about the integration of time into GIS can be consulted in Ott and Swiaczny (2001), a work including additional case studies for several thematics.

Discussion around the concept of 'time' in geomatics is complex and unending. Decisions about temporal scales and temporal steps are a common problem in modelling environmental dynamics. The notion of 'granularity' (Claramunt 1994, Paque 2004) or the concept of a 'spatiotemporal continuum' (Christakos et al. 2001) are still some of the points of contention in the question of how to integrate time into GIS. In 1998, Molenaar discussed the need of linking the spatial and temporal character of the geographic phenomena in order to better develop GIS theory and tools. One of the great challenges of spatial information science at the end of the 20th century was the development of methods on a more abstract level able to represent spatio-temporal phenomena adequately so as to describe correctly changes in space over time.

The description and characterization of changes (*spatio-temporal analysis*) have a long tradition in the more integrated functions of GIS, but also in remote sensing techniques. Precisely, one of the best contributions from remote sensing for environmental analysis is its capacity for monitoring dynamics processes. Multi-temporal functions, applied to satellite imagery to detect changes (Chuvieco 2006, 2008), have proved their adaptability and power to understand temporal phenomena.

The possibilities of GIS and remote sensing to process spatio-temporal databases exceed the capabilities of the analytical step. It is at this point that we can talk about *modelling,* and the more important objective in environmental modelling must be "finding simplicity in complexity" (Wainwright and Mulligan 2004). We will think about what a model is in Sect. 1.2.1. At this point we want to retain two different concepts of models. First, a model is a representation of a real phenomenon (any data or map can be a model and it can offer knowledge about the system to be modelled). The explanation for environmental change models may be only visual or they may be automated analyses of multi-temporal images, which monitor the process (Skidmore 2002) and, in such cases, explanatory models are confused with the classical spatio-temporal analysis process. DeMers (2002), argues that spatio-temporal modelling is more than just map algebra functions and traditional cartographic modelling. Another viewpoint, particularly in geocomputation, is that a model is a mathematical abstraction for understanding the system and also for simulating how they run over time (Coquillard and Hill 1997). Atkinson and Martin (2000) linked spatio-temporal modelling to cyberspace, as a more developed step in the conception of time simulation and projection.

Nowadays, the most common GIS and RS software have incorporated modelling functions. Different types of modelling approaches are implemented in many accessible tools. Some of them are relativity easy to use, while others first require a more theoretical approach. This will be discussed further in Sect. 1.2.2. GIS and simulation models are often proposed as an integrated tool (a 'vertical' module) to resolve conflicts in sustainable development (Giacomeli 2005). Other authors, contemplating about modelling for simulation and prospective scenarios, often call this a 'spatial decision support system' (SDSS), in which a standard GIS is complemented with some additional software components to facilitate decision support (Bregt et al. 2002).

This succinct overview may explain the rapid evolution of modelling research in the last decade.

1.1.2.3 For what? (Outcome): Modelling for simulation

Environmental phenomena are inherently dynamic and a static representation or a descriptive model alone can't cover the system's dynamics and complex processes (Batty 2003). We call modelling for the purpose of simulation/prospective scenarios the spatio-temporal models group, which not only focus on an explanation and/or analysis of temporal changes, but also provide solutions to simulated time changes.

In order to grasp the notion of modelling Bregt et al. (2002), in particular with their second *(What is changing where?)* and their third question (*What will be where?)* discuss the configuration of spatial data at time intervals and the applications of models for space-time data. "Combinations of data, representing the initial status, and some rules or models describing the change of the environment over time, are needed. These rules range from relatively simple expert tables describing change in discrete intervals over time to complex dynamic simulation models describing change at continuous time intervals…" (Bregt et al. op.cit.). Thus these authors think that, in practice, it is impossible to answer this question with any great precision.

That is one of the most evident conclusions in spatio-temporal modelling. The results, quantitatively complex and often abstract, are perhaps close to reality, but the objective is rather the design of possible lines of development, by the form of scenarios, than a real prediction of future evolution.

But what are we looking for when applying a simulation model? We will find different kinds of answers or, more precisely, several news questions:

- *What can I obtain?* In other words: what kind of results can be attained by a spatio-temporal model? There are several terms like *prediction* or *scenario* related to the notion of *simulation* and, sometimes, they aren't clearly differentiated in their use.
  - *Simulation*: It is the more general word to designate the result of a time projection model but also the process to do so. Some authors give the same significance to the terms 'model' and 'simulation' while other note the difference between them. We lean towards the definition of Hill (1993 quoted in Coquillard and Hill 1997) that states that simulation is different from modelling in that simulation is always time-embedded. "Simulation consists to make evolving a system abstraction over time so as to understand the functioning and the behaviour of the system and to grasp some of its dynamic characteristics with the aim to evaluate different decisions." (Coquillard and Hill op. cit.). Simulation can be obtained for a present situation (in order to compare with reality and to validate the model), past situation (to understand a historic evolution) or future evolution. However modelling is a popular term and many authors use it in the sense of simulation.
  - *Prediction:* A simulation may be done for an interval of time, for which starting and ending points are known (interpolation). On the contrary, prediction is time extrapolation and the –predicted– result shows what will happen at an unknown moment, generally in the future (prospective simulation).

  - *Scenario*: In simple terms a scenario shows, an opposition to the term prediction, what *can* happen. Commonly modellers apply different underlying conditions (such as macroeconomic parameters) or dynamic variables (that are changing during the simulation) so that the simulations diverge in results, which describe a framework of possibilities providing predictive answers.
- *For what?* Outcomes of the simulation/time projection model can be split into different groups; they are all partially overlapping.
  - *Knowledge objective*: Understanding temporal processes is one of the objectives of a simulation model. Here simulation is used to better understand a phenomenon and its evolution. The model is like an 'intellectual crutch,' which aids in greater comprehension of complex processes. Retrospective simulation projection used to add the territorial dimension to historical studies (See Chap. 9) is an example for this outcome.
  - *Methodological objective*: Some works focus on testing tools, comparative methods or result validation. The aim is to use the model *sensu stricto*. These studies are helpful to define the degree of possible generalization of a model or method, its thematic application domains and required data. In other words, this type of work has it in mind to perform metadata for models.
  - *Operational objective*: simulation of the future or prospective modelling, which seek practical applications such as prediction. Getting a probable image of a future situation and being able to estimate its likelihood is a powerful form of decision support. Forecasting negative impacts in order to avoid or to mitigate them becomes everyday work in many domains (natural and technological risks, weather forecast, environmental impact studies) from the local scale to global scale.

1.1.3 Opportunities

This book is the result of collaboration between several research groups and built on the contact between scientists, who work in the same field. Modelling environmental dynamics using geomatic tools leading to simulations – either prediction or scenarios – is our central focus. In Part B, the chapters (case studies) include all model types, and are written in a consistent and simple presentation. The topics include environmental objects and application area, modelling approaches, (geomatic) tools, results (simulation, scenarios), validation and a critical discussion of results.

This work is the continuation of a line of research, in which the spatio-temporal model's application is more and more developed in the context of environmental sciences. It is also necessary to refer to some earlier studies and books, which have enriched our contribution and whom we gratefully wish to acknowledge. Among numerous works we especially wish to note the following sources.

- First, the earliest books on environmental modelling using GIS are some of the most important in this thematic: Goodchild et al. (1993, *Environmental modeling with GIS)* and Goodchild et al. (1996, *GIS and Environmental modeling: progress and research issues)*. In 1993, the authors said, "This book is for researchers, academics, and professionals with geographic information systems (GIS) experience who need to know more about environmental modeling. It is also intended for environmental modelers who want to know more about GIS, its advantages, and its problems…" In almost fifty contributions, the authors provide a complete overview of the technical aspects of environmental modelling, spatial statistics and thematics illustrated by case studies. In the work of 1996, ninety contributions concentrate on environmental databases and environmental modelling linked or built with GIS. Both works are a constant reference in bibliographies, even if time (modelling in the simulation acceptance of the term) is not always at the centre of interest.
- Coquillard and Hill (1997, *Modélisation et simulation d'écosystèmes. Des modèles déterministes aux simulations à événements discrets*) offer in this book an in-depth reflection on methodological questions in ecological models. Their model's classification is a reference for a better compression of these tools. The completed sorting of modelling methods remains relevant today, even as artificial intelligence-based approaches became very popular during the last ten years and branched into different areas showing substantial progress.
- Briassoulis (2000, *Analysis of Land Use Change: Theoretical and Modelling Approaches*) offers a theoretical and methodological reflexion about the models applied to land use change. Her model classification gives a complete overview of the variety of approaches, from statistical and econometric models to spatial, optimization and integrated models. Several GIS linked models are similar to our objectives.
- In 2002, Skidmore published *Environmental modelling with GIS and remote sensing*, which is focused on the information and how the information is used in environmental modelling and management. Different chapters show data and application to global and thematic environmental models (vegetation, biodiversity, hydrology, weather, natural hazards, environmental impact and land use planning, etc.). This work

also includes a more methodological chapter where the authors propose a taxonomy of GIS environmental models and the conclusions of the principal problems in the use of GIS and remote sensing for environmental modelling. Perhaps the principal difference between this book and our work is that case studies in Skidmore focus more frequently on explanation rather than on time projection.

- DeMers (2002, *GIS modeling in raster*), supplies a synopsis about raster representation specific tools to process cell data. He shows that spatio-temporal modelling is more than map algebra functions.
- Brimicombe (2003, *GIS, Environmental Modelling and Engineering*), provides a technological vision about complementarities between GIS, simulation modelling for environmental problems and engineering. The author demonstrates how GIS and simulation modelling are joined and consequently offer "…tremendous possibilities for building versatile support systems for managing the environment…" Case studies complete this work, in which the spatio-temporal component is always present and methodological questions such as model validity are discussed.
- The work of Kanevski and Maignan (2004, *Analysis and modelling of spatial environmental data*) mainly focus on geostatistics and spatial prediction modelling. Authors show methodological aspects like monitoring network analysis, artificial neural networks, support vector machines, stochastic simulations and GIS tools. They apply these concepts to environmental data but the time aspect and validation of results are not major considerations.
- Wainwright and Mulligan (2004, *Environmental Modelling: Finding simplicity in complexity*) published a book about simulation models: "Central to the concept of this book is the idea that environmental systems are complex, open systems. The approach that the authors take is to present the diversity of approaches to dealing with environmental complexity and to encourage readers to make comparisons between these approaches and between different disciplines...." Keeping this in mind, their chapters focus on an overview of methods and tools, calibration, validation and errors in modelling, the future of environmental modelling and offer several contributions related to various thematics (climatology, ecology, hydrology, geomorphology and engineering spatial modelling and GIS), some of which are more methodological, while others are for management. Perhaps, such as in other works, it lacks in the consideration of time in modelling.
- Recently Petry et al. (2005, *Fuzzy Modeling with Spatial Information for Geographic Problems*) presented an interesting work about how fuzzy logic and fuzzy modelling are useful in modelling spatial data. They

provide solutions for geographical applications especially if limits of geographical entities are continuous rather than discrete.

This book, based on the advances summarised in the above-mentioned publications, intends to give an actual overview about geomatic models applied to simulate environmental dynamics and particularly focuses on methodological aspects, such as model calibration and validation.

1.2 Modelling approaches

Among the variety of modelling approaches, the authors deliberately restrict the panel of methods and software implementation to those which deal with both space and time. For instance, a lot of models developed in economics, medical diagnostics or engineering, are outstanding but don't take up time. The explicit inclusion of the spatial dimension is essential to tackle environmental dynamics and to select criterion for here presented – and further implemented – modelling approaches.

An important issue is the concept of time and space – continuous or discrete – reflecting a fundamental discussion in geography and digital representation of data in GIS (raster versus vector). The temporal aspect, particularly the notion of temporality, temporal scales in environmental dynamics and the idea of granular time is discussed, among others, by Coquillard and Hill (1997) and Worboys and Duckham (2004).

What's a model? A variety of definitions exists. The most basic of them states that a model is a representation of a real phenomenon. This means that any data or map is a model. In geomatics, the common definition includes the behaviour of the phenomena to be simulated. Following this train of thought, a model is a functional representation of reality able to help us in understanding its action or predicting its behaviour. Minsky (1965) already insisted on the functional aspect by defining a model: "To an observer B, an object A* is a model of an object A to the extent that B can use A* to answer questions that interest him about A." By insisting on processes rather then the form, the term model is closer to the notion of a system, which is defined by functional concepts like relationship, feedback, system effect (the difference between cumulative proprieties and constitutive proprieties), hierarchic organisation and complexity, which means that we don't have an exhaustive knowledge about the modelled object. The outcome use of a model may be a gain in knowledge or decision support. The first one aims at scientific progression in the understanding of complex phenomena, while the second one specifies a practical objective in management processes like risk prevention or land planning tasks. Some authors distinguish between modelling and simulation. Simulation explicitly refers to the temporal dimension and means model behaviour during a time period which may be prospective. A simulation means creating an evolving system abstraction over time to help us understand system behaviour, how a system works and some of its dynamic characteristics with the aim of evaluating different possible decisions (Hill 1993).

An important issue is the performance of a model. We will return to this aspect in the fourth section about model calibration and validation. Here we only want to point out that the relationship between the complexity of a model and its performance is not linear. A model is a simplification of reality. The temptation to make a model more complex in order to enhance its performance is great. Coquillard and Hill (1997) even noticed that adding of new variables and additional weights doesn't necessarily signify a proportional gain of knowledge and facilities in the model validation. They even demonstrated that trying to increase model complexity may decrease the model efficiency (difficulties to control the model, to validate its results). Also the complexity of the computing implementation increases in the best case scenario linearly with the model complexity; however this augmentation may be exponential.

The following pages give a concise presentation of common methodological approaches used to model environmental dynamics. The material of the second section is an overview about the practical implementation of models: available software. Finally, a critical point will be discussed: the calibration and validation of models.

1.2.1 Methodological overview

Model typologies may be based on various criteria such as the modelling objective (descriptive, explanatory, predictive, decision support), the underlying methodology, the spatial and temporal explicitness (the spatial and temporal levels and resolutions taken into account), the types of environmental dynamics considered, etc.

Briassoulis (2000) presents a chronological literature overview of model typology schemes: "Wilson (1974) proposes a classification scheme based on the dominant technique used in model building (pp 173-176). Batty (1976) distinguishes between substantive and design criteria for model classification (pp 12-15). Issaev et al. (1982) mention four possible approaches to model classification: (a) construction of a list of attributes characterizing aspects of the models, (b) specification of a set of criteria serving as a general evaluation framework, (c) construction of an 'ideal' model as a frame of reference for judging all other models, and

(d) cross-comparison of models on the basis of general structure characteristics of these models (Issaev et al. 1982, 4). Stahl (1986) suggests a number of substantive criteria for classifying business location models including issues of theory and model purpose (Stahl 1986, 769-771)."

Choosing the methodological criterion, the literature suggests a variety of typologies (among others Coquillard and Hill 1997, Kanevski and Maignan 2004). Generally authors distinguish between deterministic, stochastic and artificial intelligence based models, a group becoming ramified during the 1990ies into several branches like cellular automaton, multi agent systems and neural networks. In practice, we often notice combinations of two or more approaches. Also models are frequently enhanced by, not presented in this chapter, methods like macroeconomic approaches (Verburg et al. 2006b) or expert systems (Giarratano and Rilay 2005). All of them are very useful and interesting and their practical interest may be estimated by reading the following case studies. Nonetheless any of them includes explicitly space. Other methods, for example decision support techniques like multi-criteria evaluation and multi-objective evaluation (Eastman et al. 1993) deal with space but are designed to perform suitability maps that may be used in simulations, and some authors did so (see Part B).

1.2.1.1 Deterministic models

Using a mathematical formula, the modelled object is entirely described excluding any probabilism. Most of them, handling with continuous space and time and resolved differential equations, are also called analytic or mechanic models. Their mathematical rigour facilitates implementation but also limits their area of application, generally restricted to a high level of system abstraction. A famous example for analytic models is Odum's Silver Springs model (Odum 1957) applied to energetic ecosystem flows at a global level. Only a few deterministic models include a spatial variation like competition models (Tilman 1977, Huston and De Angelis 1994). The principal limits of deterministic methods in modelling of environmental dynamics are the poor degree of spatialization and data uncertainty. Generally deterministic models consider the space homogeneous; a hypothesis which rarely matches with reality. Also complex dynamics often contain uncertainty including data with a low level of confidence but also ignored or unknown variables.

1.2.1.2 Stochastic models

They are also called probabilistic models. If the model is evolving in time, which is considered discrete, we also call them stochastic simulation or Monte Carlo models.

The basic idea is that observation reflects the realisation of a system state among possible states. The list of possible states is known and finite. A famous illustration is throwing a dice. Each throw realizes one of the six possible states which are, for an instant t, exclusive and time independent. Consequently, it is a random or stochastic variable. The successive realisations form a discrete process. This means that the variable can not change continuously in time but only into an ascending series of real positive numbers called instants. The system state only changes from one instant to the next. Because we deal with a random variable, deterministic approaches can not model this process. Considering time as discrete offers a lot of advantages. So the model may be performed for specific time scales, events or activities. Discrete modelling (some authors prefer the term simulation) became powerful with the development of object based languages such as C++ (Bouzeghoub et al. 2000, Frihida et al. 2002).

The applications of stochastic models are numerous. The Monte Carlo simulation is known since the 1950's (Metropolis and Ulam 1949) and based on a random number generator with the aim to model systems, which elements are insufficiently known and may be approached by probabilistic.

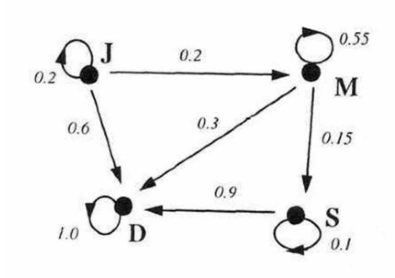
- Markov chain analysis (MCA)

Today, Markov chain analysis is one of the most used stochastic approaches in ecological and environmental modelling. The mechanism of Markov chain analysis may be introduced by an example developed by Coquillard and Hill (1997): the observation of the development of a population in time. The individuals of the population may belong to four different states: juvenile (J), maturity (M), senescence (S) and death (D). Fig. 1.2 gives an illustration of these states and transition probabilities.

This Markov chain is qualified first order as a stochastic and discrete process with a finite number of states and the probability that the system realizes a given state at instant t+1 depends only on its state at instant t. This means that it is possible to predict a variable knowing only its actual state. Consequently the specialists qualify a first order Markov chain as a stochastic model *without* memory – a severe restriction in modelling environmental dynamics that generally need a detailed historical knowledge.

Markov chain became a popular tool for a large spectrum of environmental applications but also in image processing (Flamm and Turner 1994). The number of publications about land use/land cover changes (LUCC) calling on Markov chain analysis is vast. We can only give some examples. Lippe et al. (1985) uses Markov chains to model heathland succession. Logofot and Lesnaya (2000) discuss their application in forest dynamics and Balzter (2000) is resuming the prediction power of more than 20 Markovian models applied to grassland ecosystems. Tucker and Arnaud

(2004) use this methodology, always without a spatial component, to study vegetation recolonisation and restoration. Markov chains were also proposed as a possible modelling approach in the LUCC program (Nunes and Augé 1999). Finally, some research (Roman 2004) emphasizes the advantages obtained by coupling deterministic and stochastic models.



Final states

		J	M	S	D
Initial states	J	0.2	0.2	0	0.6
	M	0	0.55	0.15	0.3
	S	0	0	0.1	0.9
	D	0	0	0	1.0

Fig. 1.2 Time transition for a given population with four possible states (nodes) and probability transitions (arcs) represented also (on the right) as a transition matrix. Coquillard and Hill 1997 (modified)

The main restrictions of Markov chains are, once more, intrinsic. Coquillard and Hill (1997) outline their independence from time (model without or with little memory, dependent upon Markov chain's order) and, particularly, their independence from space (such as for deterministic models). Space is neither homogenous nor isotropic. So the probability that a pixel becomes reforested depends, among other parameters, on its distance to existent forest limits but also to isolated trees, topographic conditions and wind directions.

1.2.1.3 Artificial intelligence based models

The literature gives different definitions of artificial intelligence (AI), some more restrictive than others. Particularly, the question of whether cellular automata belong to AI continues to be controversial (for instance: Langlois and Philipps 1997, Lee 2004). In this context, we will simply consider that AI based systems are computer programs simulating the human brain processing or other complex mechanisms. Some authors also qualify the modelling approaches using AI as artificial life. All modelling approaches based on AI use the concept of knowledge. The origin and enhancement of knowledge may be added or self-learned. Added knowledge means that knowledge comes from external sources and generally provided by databases. This is the case for cellular automata, expert systems and multi-agent systems. Some authors call this distributed artificial intelligence.

Self-learning AI also need a basic, added, knowledge to initialize the model but the model produces and enhances the knowledge by itself: neural networks, cognitive and endomorph multi-agent systems.

The development of AI is closely related to that of computer science. Among fundamental research, we note the publication of Alain Turing (1950), considered a founder of AI *Computer machinery and intelligence* and the important advances performed by Marvin Minsky *Matter, minds and models* (1965) and *Society and mind* (1987). Since the 1980's an important effort has concerned the relationship between modelled components, which become more autonomous.

- Cellular automata (CA)

The development of cellular automata (CA) is built upon the advances by Ulam and Von Neumann (Von Neumann 1966), Burks (1970) and Gardner (1970, 1971).

A CA is a system that has components that are interacting at the local level according to elementary rules to simulate a complex and dynamic system over space and time. Space (the cellules), their state and time are discrete (Wolfram 1985, Jen 1990). Langlois and Philipps (1997) complete this definition with a description of AC structural and functional proprieties.

  - The structural proprieties define the topology of the cellular grid, which is generally a raster grid. Most of them have two dimensions (raster image) linear or volumetric applications or n-dimensional AC's are possible. The structural proprieties also depend on the form of cellules, usually square or hexagonal, and, consequently, on the number and quality of cellular connections (contiguity and number of neighbours). Like the filter techniques, the grid border management is also a critical aspect. GIS implementation of AC commonly does not allow toric grids. So border pixels are excluded or surrounded by virtual pixels. Another possibility is to anchor the active matrix into a wider, passive, environment; a solution often selected in fire simulation models. Finally, we can distinguish between AC's that only consider the direct vicinity and AC's handling with larger spatial interactions, usually weighted by distance.
  - The functional proprieties are a list of discrete states that a cellule may realize and transition rules. They are also called evolution rules of the automaton. These rules, rather stochastic than deterministic, configure the state that the cellules become during the simulation (Mezzadri-Centano 1998).

The AC characteristics may be illustrated by the famous game of life invented by Conway (Gardner 1970), thought to be the ancestor of AC.

Conway's AC had a toric matrix with square pixels that may be dead or alive depending on very simple transition rules. The initial conditions are random.

The cellular interaction needs, at least in theory, a parallel processing (Tosic and Agha 2003, 2004a, 2004b). With sequential computers parallelism is simulated by either synchronic or asynchronic activation. The more cellule categories (possible states) there are, the more complex AC modelling becomes. Objective conflicts in space colonisation need a form of arbitration like random decision, probabilities or refereeing based on extended vicinity characteristics. So a somewhat realistic AC application needs an immense computational volume. Zeigler (1976) already intended to optimize AC processing.

AC's applications in environmental geography are very numerous, therefore we will only mention a few examples. Elmozino and Lobry (1997) and Dubé et al. (2001) use AC for forest simulation. Jacewitz (2002) and Wu and Marceau (2002) employ AC to answer ecological questions and Engelen (2003) for LUCC. But it is in urban geography that AC has become a major modelling approach, which takes advantage of theoretical advances like the studies of Forrester (1969) and Tobler (1979). Langlois and Philipps (1997) give an overview of AC applied to urban dynamics that may be updated by the publications of Batty and Xie (1999) and Yeh and Li (2001).

- Multi-Agent Systems (MAS)

In plain text, multi-agent systems (MAS) may be described as a sophisticated extension of a cellular automaton responsible for socializing the cellules. MAS, also called distributed artificial intelligence, have more individualised components, which are within in systemic interaction. The components, called agents, are autonomous and organised according to social rules. Ferrand (1997) states that the agents are endowed with a quantitative and qualitative state and transitions (both discrete). Simultaneous interactions (parallel processing) occur between them (internal or social), but also with external stimuli (data input or system environment processes), which are also called perceptive interactions. The social agent structure is based on behaviour rules and outcome that may be explicit (like for AC) or emerge from the simulation (Briot and Demazeau 2001). In the latter case, they call them reactive agents, which require memory and knowledge about the other agents. Some authors call them cognitive agents (Franc and Sanders 1998, Bousquet and Gautier 1999).

The computer implementation usually uses object languages and a wide range of scripts are available today.

MAS is also useful for a large range of applications: simulation of complex systems (Savall et al. 2001), LUCC (Parker et al. 2001, 2003), generalisation of urban topographic maps (Ruas 1999, 2002), landscape and farming simulation (Poix and Michelin 2000). MAS are also often used in participatory modelling (Castella et al. 2005, ComMod 2005).

The limiting factors are the great amount of processing time and difficulties in validation of modelling results. As early as 1997, Ferrand deplored the lack of tracking in MAS.

- Neural networks (NN)

Neural networks (NN) are inspired by the workings of the human brain and characterised by parallel data processing and the ability to enhance its knowledge itself. Most of them are synchronic and deal with discrete time. Each elementary neuron calculates a single output depending on the input information. A neuron may receive information from several upper neurons. Depending on signal force, transfer function and activation sill, an upper neuron is activated or not (Fig. 1.3). The neurons are connected hierarchically as a network that works like a black box. The training of a neural network is a critical point. Using a training data base the network is configured, reflecting the initial conditions of the simulated system, so as to optimize the network by a set of weights. NN became very popular in the last few years because they are general, non-linear estimators that may be used in many disciplines (Villa et al. 2007). At the end of the 1990's, they were often applied in recognition tasks and signal processing, predicting applications based on time series (Bishop 1995, Parlitz and Merkewirth 2000, Lai and Wong 2001).

The origin of neural networks is old as the work of James (1890), which presented the idea of the associative memory. Hebb (1949) returned to this concept as a training model for NN: Hebb's law. Rosenblatt (1958) designed the first neural computer, called perceptron, it was applied to the recognition of forms and was later enhanced by Widrow and Hoff (1960). Hebb's law is important in the understanding of the independent learning ability of neural networks. Hebb (1949) said that than an axon connecting neuron A with neuron B by a synapse is often excited, thus the quality of this connection becomes different so that the signal flow becomes easier. In artificial neural networks, this repetition effect is simulated by a weight, which is changing during the training period. Consequently, the training of the network is supervised. The second important point is that of the connecting structure of the network: its topology. Simple networks (like Hebb's one) have only two layers. All neurons of the input layer are connected with all neurons of the output layer. There are no connections between neurons belonging to the same layer. Today, researchers usually design multilayer networks with at least one hidden layer. This multilayer perceptron preserves the hierarchical connecting design and was used in statistics as early as the 1960's (Davalo and Naim 1969).

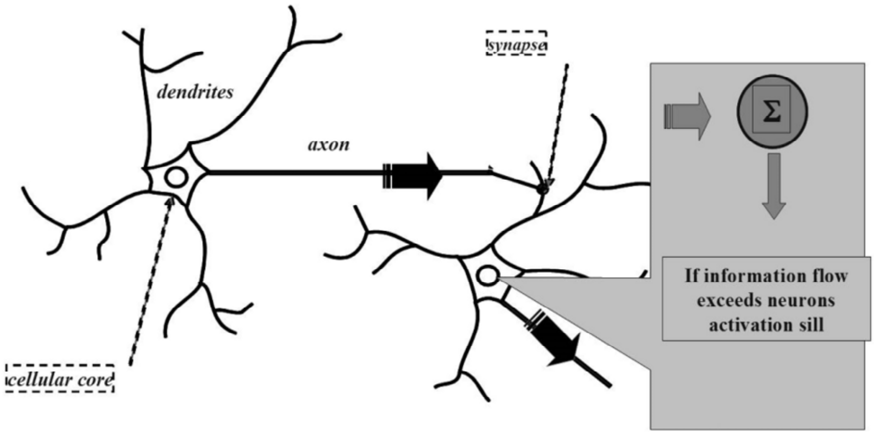


Fig. 1.3 Architecture of a neural network

Since the 1980's, NN applications have really taken off with the introduction of powerful computers. In geography and environment research, we notice a delayed use of NN in comparison with other methodological approaches (end of the 1990's).

1.2.1.4 Fuzzy logic

The concept of fuzzy logic may be introduced as an extension of classic Boolean logic with the aim of handling non-binary data and especially occurrences of data uncertainty or phenomena of partial truth. This means that the logical evaluation gives a result neither entirely false nor entirely true. A famous illustration of this concept is the perception of temperature classes (Fig 1.4). Fuzzy logic deals with reasoning that is approximate rather then precisely deduced from classical predicate logic. The concept of partial truth or degrees of truth is often confused with probabilities. Fuzzy truth expresses a membership to an imprecisely defined set, not likelihood or conditional membership.

The fuzziness of geographical data is related to the imprecision in the location and boundaries and also to uncertainty and gaps in attribute data. The origin of fuzzy logic is associated with Lotfi Zadeh's research, particularly his sub-set theory (Zadeh 1965) and his theory of possibilities (1978). The first one led to the membership function (e.g., Fig. 1.4), the second theory on the possibility function is associated with the fuzzy command. Real variables are transformed into fuzzy variables belonging to their fuzzy set membership function. Among others Tong-Tong (1995) furnishes an introduction to the fuzzy logic concept.

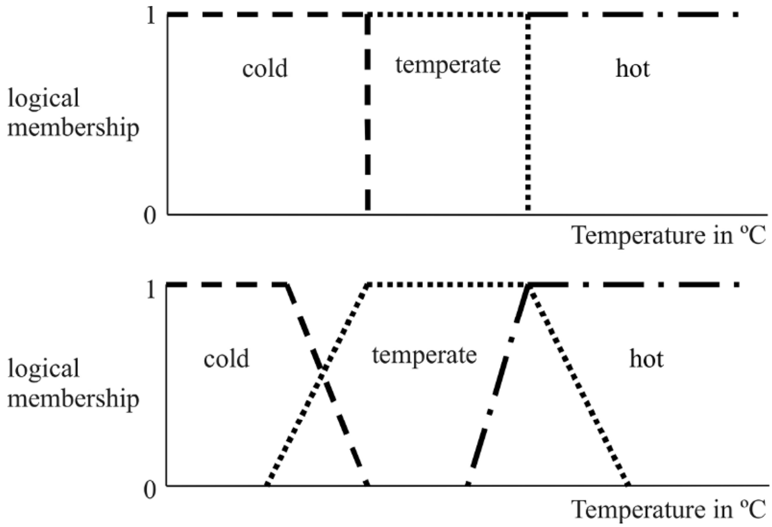


Fig. 1.4 Subset theory and membership functions in Boolean logic (above) and fuzzy logic (below)

A great deal of research has been developed based on fuzzy systems to solve problems related to geo-processing (e.g., Bouchon-Meunier 1995, Dragicevic and Marceau 2000). According to Saint-Joan and Desachy (1995), fuzzy systems deal with imprecise and uncertain information in a more efficient way than algebra map systems based on Boolean logic. Many authors point out some advantages in the use of fuzzy inference systems to solve problems associated with the environment (Centeno and Góis 2005, Schultz et al. 2006). In decision support, the integration of heterogeneous data creates a trade-off between favourable and unfavourable conditions. Fuzzy logic also allows a standardisation of the original data units in order to process them together. Using fuzzy logic, the aim can be focused onto specific regions of interest. Fuzzy reasoning can be used as validation tool, reducing the abrupt spatial difference between false and true. Petry et al. (2005) provided an up to date and complete overview of the methodological aspects in fuzzy modelling and its usefulness for geographic problems.

1.2.2 Modelling tools

The practical implementation of modelling concepts and methodological approaches may be undertaken using two different methods. The first one consists in using modules included in available GIS software. In opposition the second method uses a specific model designed with general tools such as computer languages, macro languages or more general statistic programs like SPLUS or Matlab. Halfway between these methods some program platforms exist, offering a wide range of scripts and libraries. In this section, we succinctly describe the characteristics of the most well-known GIS software that include modelling tools.

Among GIS software, ESRI products (ArcInfo, ArcView, ArcGis) are commonly used. Recent editions of ESRI software include a lot of modelling tools. Some of them are not included in the basic software but in complementary modules. This is the case of the Land Change Modeler, a software extension to ArcGis available since summer 2007, which is developed by Clark Labs first for their own GIS software: Idrisi, a universally used GIS and image processing software. Particularly, its last edition (Idrisi Andes) offers a multitude of modelling tools:

- LCM (Land Change Modeler): LCM is the new integrated modelling environment of Idrisi Andes (Eastman 2006) including tools for analysing the past land cover change, modelling the potential for future change, predicting the phenomena evolution, assessing its implication on biodiversity and ecological equilibrium and integrating planning regimes into predictions. The first step is a LUCC analysis and performing of LUCC budgets. The second step is the modelling of transition potentials. To do this, the dynamics are split into sub-models (transition form one land use/land cover category to another). Each sub-model is described by relevant criteria. The quantitative variables can be included into the model either as static (unchanging over time) or dynamic factors. The dynamic variables change over the training and simulated period and are recalculated for each interaction during the course of prediction. The transition potential maps may be calculated by using a multi layer perceptron or by logistic regression. Then, the established knowledge about the land cover transitions is used to forecast prediction, a simulation step performed either by Markov chain analysis or by an external model. The spatial allocation of predicted transition amount may be influenced by dynamic variables, infrastructure changes and zoning. The results may be used for ecological sustainability and land planning scenarios.
- GEOMOD: Geomod (Pontius et al. 2001) is a LUCC simulator modelling the transitions from one land use to another (e.g., from forest to non-forest). To do so, GEOMOD needs as start-up information the beginning and ending time of the simulation, the coverage with the initial state of the two categories, the land surface area changing in use, land use change drivers and a stratification map. A suitability map may be produced from driver information or supplied (external), particularly by multi-criteria (MCE) and multi-objective evaluation (MOLA) modules.

These are decision support tools also frequently used with CA_MARKOV (see below). The stratification map allows the division of the study area into several regions. Each region only allows one transition direction. GEOMOD includes the possibility of restricting possible transitions, by simple filter, to the neighbourhood of occurring land use at the start time. GEOMOD is designed to predict the location of LUCC, not the quantity of the changing area.

- CA_MARKOV: This tool is an integrated tool calling for Markov chains analysis (MCA) for time prediction and Multi-Criteria Evaluation (MCE), Multi-Objective Evaluation (MOLA) and cellular automata to perform a spatial allocation of simulated land cover scores. MCA of second order is a discrete process and its values at instance t+1 depend on values at instances t0 and t-1. The prediction is given as an estimation of transition probabilities. MCA produces a transition matrix recording the probability that each land use/land cover class might change into each other class and the number of pixels expected to change. MCE is a method that is used to create land use/land cover specific suitability maps, based on the rules that link the environmental variables to land use/land cover and its dynamics during the training period. These rules can be set integrating statistical techniques with a supervised analysis performed by the modeller. The suitability maps are used for spatial allocation of predicted time transitions. A multi-objective evaluation module and a cellular automaton are performed to resolve objective conflicts between land use/land cover classes or categories and to improve the spatial contiguity in the final prediction map.

GRASS (Geographic Resources Analysis Support System) is freeware and open source software, which is used particularly in erosion and rainfall-runoff modelling, hydrological modelling and landscape analysis. Detailed information is available online on the GRASS homepage.

CLUE (Conversion of Land Use and its Effects) was developed by Wageningen University in the Netherlands. CLUE, also freeware, is a dynamic and multi-scale LUCC model tool basing on concepts like connectivity, hierarchical organisation, system stability and resilience and a large range of driving factors. The prediction step is performed by statistical regression. More information about the concept and applications of CLUE can be found in Verburg et al. (2002).

LTM (Land Transformation Model), also freeware, is a software designed by HEMA (Human-Environment Modelling and Analysis Laboratory) belonging to the Department of Forestry and Natural Resources of Purdue University in Indiana, United States. LTM combines GIS and remote sensing tools with neural networks and geostatistics to forecast land use changes.

DINAMICA, freeware, is developed by a research team of the Remote Sensing Center of the Federal University of Minas Gerais, Brazil. The latest release, DINAMICA EGO (Environment for Geoprocessing Objects), aggregates traditional GIS tools with specific simulation modules designed for complex spatial phenomena. The model, from calibration to validation, follows a data flow in the form of a diagram; a friendly graphical interface permits the creation of models by connecting algorithms via their ports, likely the Macro Modeler in Idrisi. DINAMICA offers the possibility to divide the test area into sub-regions, characterised by different environmental dynamics, and apply a specific approach for each one of them (Rodrigues et al. 2007). The calibration step produces a probability map of occurrence for each transition, using the weight of evidence method. DINAMICA uses two complementary transition functions: the Expander and the Patcher. The first process is dedicated only to the expansion or contraction of previous patches of a certain class. The second process is designed to generate new patches through a seeding mechanism. The combination of DINAMICA's transition functions presents numerous possibilities with respect to the generation of spatial patterns of change. Model validation is based upon the fuzzy similarity, which takes into account the fuzziness of the location and category within a cell neighbourhood (Hagen 2003).

SLEUTH, developed by Clarke (Dietzel et al. 2005) at UC-Santa Barbara, is a software with two components: the Clarke urban growth model (UGM) and The Deltatron Land use/Land Cover model (DLM). SLEUTH uses cellular automata and is principally applied to urban growth modelling.

Land Use Scanner and Environment Explorer are modelling software developed in the frame of the LUMOS consortium – a platform for land use modelling in the Netherlands bringing together public agencies, research centres, university and private enterprises in the Netherlands. The Land Use Scanner calculates future land use change on the basis of land use scenarios (demand on space) suitability maps and attractiveness criteria. The Environment Explorer is a multi-scale dynamic model to perform land use scenarios for the Netherlands. Viet (2006) gives more detailed information about the Environment Explorer, Kuhlmann et al. (2005) about Land Use Scanner.

MOLAND (Monitoring Land Use/Cover Dynamics) is a research project carried out at the Institute for Environment and Sustainability – Land Management and Natural Hazards Unit form the Joint Research Centre (IRC) of the European Commission. Based on cellular automata, its aim is to provide a spatial planning tool for assessing, monitoring and modelling the future development of urban environments (EUR-JRC 2004). A particular focus is the analysis of fragmentation in urban landscapes.

The call on additional predictive models or specific computer software became a common practice to resolve particular modelling aspects mainly in physical geography. We also notice a ramification of spatial distribution modelling tools (Bioclim, Domain, ENFA, GARP, MaxEnt) that may be connected, during the modelling process, to GIS based modelling tools (See Chap. 11). MaxEnt (Maximum Entropy), applied generally to geographic distribution questions (Phillips et al. 2006), is a representative example for new modelling tools trying to preserve as much of the uncertainty of the original data as possible.

As mentioned, a lot of models are self-made and designed without using standard available GIS software. Typically they call on already written scripts for statistical software or computer languages. The following case studies (See Part B) give a survey about the range of possibilities to proceed in this way.

1.2.3 Model validation

Model validation clearly is a critical point. Even if it occurs as the last step in the modelling chain, it has to be placed in the general modelling context.

Whatever the methodological approach is, the general modelling procedure begins with the definition of the model objectives and the initial hypotheses. The next step consists in collecting the relevant and available data, their description and definition (metadata) but also the knowledge about system behaviour and the underlying model and the simplifying restrictions. Often a graphic representation is used to guarantee a synoptic overview of this conceptual process. The following steps are the computer implementation of the model, its initialisation, running and the validation of performed results.

The model credibility depends on its validation. Following Coquillard and Hill (1997) referring to the definitions of the Society of Computer Simulation (SCS 1979), this general term may be split into three tasks:

- *Verification* - First, the modeller has to make sure that the model works accurately: correct computer code implementation, the right module interaction and insertion into the computing environment. This step is also called the internal validation. Heuvelink (1998) focuses on error propagation in environmental modelling with GIS.
- *Calibration* – The purpose of this step is to test the conformity of the global model behaviour related to the objectives. For simulation models (models evolving with time), the calibration also signifies the initialisation of the model with data and knowledge coming from a training period or training dates. In the case of predictive modelling, this means that the

model is able reproduce former and actual system states on the base of delivered information. Artificial intelligence based models also call this step model optimization by machine learning. It has to be mentioned that most of the common validation techniques are also applicable for calibration. Some authors combine verification and calibration and call model calibration the process of model design such that it is consistent with the used data for model elaboration (Verburg et al. 2006a).

- *Validation* – The aim is to improve the robustness and acceptability of the model. In the strict sense of the word, validation is the evaluation of model results accuracy. Therefore used data don't have to be known by the model. In the following paragraphs, we focus on model validation as measurement of model accuracy and correctness of model results.

Rykiel (1996) distinguishes between 'operational' (measurement of model output performance) and 'conceptual' validation. He calls the latter one the procedure to ensure that postulations underlying the conceptual model are correct or justifiable and that the model is reasonably represented compared to the model objective, the simulated system. Obviously, Rykiel's definition about conceptual validation matches with Coquillard and Hill's acceptance of verification and calibration.

A first validation may be visual. It's a more intuitive comparison method, the main feature is the resemblance between model output and the validation data, e.g. simulated land use and observed land use. However, the visual approach only gives a first impression and model accuracy has to be otherwise validated, generally statistically. Among validation methods we can distinguish principally between two branches:

- Full validation: a validation by a comparison with the real data (observed reality) is possible. A large panel of statistical tools may be used to appreciate the correctness of the model output: comparison matrix (pixel by pixel, ROC and Kappa indices, fuzzy location, spatial shape and pattern), comparative analysis of LUCC-budgets etc.
- Partial validation: a comparison between model outputs and real data is impossible. This is the situation if the model is simulating a future system state, which is impossible to validate completely for an obvious lack of real data. The validation may be tried by comparison (e.g., with an experts knowledge), by repetitiveness (stability of model outputs), by convergence (of outputs from different models).

1.2.3.1 Full validation techniques

The validation is based upon a comparison between the modelled output and real data. A classical example is a similarity test between a simulated land use and real land use at the same date. Both documents have the same nomenclature and resolution (or scale for vector map outputs). A basic validation consists in pixel by pixel assessment: a comparison matrix showing the overall prediction score and categorical error rates. Various statistical indices are available; the most well-known is the Kappa index of agreement. Pontius (2002) developed a statistical tool, implemented into Idrisi Andes, combining an assortment of Kappa indices measuring the agreement of a pair of maps in terms of quantity and quality (location). ROC (Receiver Operating Characteristic) is another statistical measurement of agreement in terms of location (Hanley and McNeil 1982). ROC differs from Kappa location index by comparing a likelihood image (e.g., a suitability image) of a land use category and a Boolean image showing where this category really occurs. To do so, ROC ranks in descending order the categorical suitability by user defined thresholds. The occurrences of each resulting class are compared to the binary real map of location. Consequently, ROC is also an excellent calibration tool because it allows for the measurement of how well a suitability map, expressing the training knowledge, matches with the initial and model known conditions (Pontius and Schneider 2001).

Most models better predict stability as change. An interesting model validation approach focuses on changed pixels: real changes (between the model's known state and a future state, unknown to the model) and simulated changes. Applied to LUCC, Pontius et al. (2004) calculate a LUCC-budget splitting changes into gain, loss, net change and swap. Swap means the changing of location for the same amount of occurrences. The comparison of real and modelled LUCC-budgets permits a more detailed understanding of model errors.

Nevertheless, the mentioned validation approaches are based on a pixel by pixel comparison and don't take into account spatial pattern, their distribution and shapes (White et al. 1997). Spatial analysis measurements are the norm in landscape ecology (Forman 1995, McGarigal and Marks 1995) and may complete the panel of validation tools.

Fuzzy logic represents a different way to escape a strict cell to cell validation. Fuzzy logic permits answering the question about the degree of agreement in location more flexibly and should be used in cases of low spatial confidence or multiple resolution data. The fuzzy comparison method developed by Hagen (2003) was incorporated in some GIS based modelling tools such as DINAMICA. The adjustment uses a declining exponential function comparing the cells classes' distribution to the pixel in the centre of the filter. Barredo and Gómez (2003), using the MOLAND (Monitoring Land Use/Cover Dynamics) model, presents a Fuzzy Kappa measure which is more gradual than the classic cell to cell comparison.

1.2.3.2 Partial validation techniques

It appears clearly that future land use/land cover, simulated as a scenario or prediction, can not be validated by classical comparison techniques using, real, but not yet available data. However, a conceptual validation and the assurance of the model's robustness may provide useful information about the model's validity. Robustness can be tested by measuring the output stability during iterative model running. The exploration of error effects in model results derived from uncertainty of input data, data weighting and transformation also provides useful information about model performance. Gómez Delgado and Barredo (2005) describe a method, which assesses the risk when using model outputs. Gómez Delgado and Tarantola (2006) propose a sensitivity analysis with the aim to test model stability. They use several indices measuring model result's variability relative to changes of the input parameters. An additional and commonly applied validation approach consists in confronting model outputs with expert opinions.

1.3 Presentation of following case studies (Part B)

The following series of contributions (See Part B), written by researchers working in Brazil, France, Italy, Mexico and Spain, attempt to show a large, but not exclusive, display of what geomatic models using GIS can provide in modelling environmental dynamics. The professional fields of the authors stretch from geography, geomatics, ecology, environmental sciences, urban development and land planning, computer science to mathematics. All of them belong either to university communities or research centres.

1.3.1 Themes and objectives

The thematic applications of the performed simulation models shown in the following pages all deal with environmental dynamics, although they are as various as the notion itself. Some authors focus on modelling of concrete environmental dynamics like deforestation and reforestation, fire risk, expansion of intensive forms of agriculture, loss of biodiversity or urban growth while other proceed to a more general analysis and simulation of land use/land cover changes related also to landscape changing.

The outcome of each contribution may be another criterion helping us to understand the set of used models and to try to classify them. One objective is what today is called participatory modelling, that is, including the opinion and knowledge of the involved (local) communities and co-operating with local participants in building prospective tools for exploring paths for sustainable development at the local scale (Guerrero et al., Cuevas and Mas, Godoy and Soares-Filho, Monteil et al.). Several articles have the aim to provide decision support for environmental management and land planning (Aguilera et al., Barredo and Gómez, Benito and Peñas, Valenzuela et al.) or with the aim to provide operational solutions (Galtié). In comparison, some papers clearly aim to make more fundamental research in model comparison and validation (Follador et al., Paegelow et al., Selleron and Mezzadri-Centeno), while others intend to reconstruct former landscapes (Camacho et al.).

In a more general sense, almost half of the presented works have a practical objective (instantaneous time modelling, decision support, participatory modelling), while the second group insists more on methodological aspects about modelling methods, simulation and scenario significance and validation.

1.3.2 Time scales

Used timescales in modelling provide one criterion more to make a typology of the following case studies.

The contribution of Galtié is based on a short timescale including actual and recent annual (last decade) data. The aim is to derive an instantaneous and quasi real-time updated level of risk, which can be used in fire risk prevention and the fight against fire. Actual data reflect the state of the main components of risk (land cover, land use, etc.). A decade training period is used to determine the terms for the component's combination and calibration (explanatory variables).

The majority of the presented work use a medium timescale: from a few decades to a century. All eleven of these contributions intend to create prospective simulations, which typically used two or three earlier decades for the training data. Some of them use more historical data, describing the modelled variable in relation to the speed of the involved dynamics. The simulations or prospective scenarios also span to a few decades (up to 2040 in Barredo and Gómez). Sometimes the simulated date belongs to the recent past. This means that the training data didn't include the most recent date, which is only used for model validation. Inside this medium timescale group, a finer classification may be obtained by focussing on the type of modelled dynamics. Low speed dynamics and/or regressive land cover dynamics are considered by Paegelow et al. and Monteil et al. The latter work may also be regarded as a transition between short and medium timescales because it uses annual training data.

But fast and progressive land use/land cover dynamics form the largest group (9 chapters). Urban growth, loss of biodiversity, agricultural intensification and deforestation are high speed processes that require a better understanding through modelling because they are directly related to global problems and what we call nowadays sustainable development.

Finally, the contribution of Camacho et al. deals with a long time span in order to perform an approximation of the historical land use. It's also the only modelling used in a retrospective way.

1.3.3 Modelling approaches and used models

When we refer to methodological modelling approaches and used models – some authors use only one approach which belongs clearly to one modelling type (e.g., cellular automata, Markov chain analysis, etc.), while others used a combination of several methods and a third group employs numerous models in order to compare them – we have another criterion, with which to classify the following works.

The contributions of Follador et al., Paegelow et al. and Selleron and Mezzadri-Centeno are based on several models with the aim to compare model outputs (simulated land use/land cover) and to enhance their validation. In concrete terms, these authors use functions included in commercial GIS software like Idrisi Kilimanjaro or Andes, in freeware software like DINAMICA and/or algorithms that they developed themselves. Applying different modelling approaches to the same study area(s) and data base(s), has the objective to improve the model's outputs by comparison and to better identify critical points and, in this way, to get more information about model ability and model generalisation.

Paegelow et al. compare a so called "combined geomatic model" (Markov chain analysis, multi-criteria and multi-objective evaluation and a cellular automaton) based on Idrisi Kilimanjaro functions with self-developed algorithms like polychotomous regression and neural network based models. Follador et al. apply the same "combined geomatic model" and made a comparison with the Land Change Modeler (implemented in Idrisi Andes), a self-made neural network (PNNET: Predictive Neural NETwork) and DINAMICA EGO. Except for PNNET, these models call on MCA (Markov chain analysis 2nd order) for computing time transition probabilities.

Another case is the work done by Benito and Peñas. The two methodological approaches – a simulator of land use change, GEOMOD implemented in Idrisi Andes, and a spatial distribution model, MaxEnt –run together and prove that their combination improves the predictive capability compared to the GEOMOD based modelling approach alone. More concretely, MaxEnt is performed to generate a greenhouse-distribution model jointly with GEOMOD to simulate greenhouse growth over the distribution model.

The other authors use one main modelling method which is, often, split into several, more or less, complex modelling steps. Here we find practical applications for commercial GIS software modules, especially Idrisi. Guerrero et al. make use of GEOMOD (Pontius et al. 2001) and Camacho et al. employ an optimisation method (Briassoulis 2000) exploiting multi-criteria and multi-objective evaluation technique.

For the research utilizing only one model, the cellular automaton based algorithms are dominant. Godoy and Soares-Filho as well as Cuevas and Mas employ DINAMICA EGO, a generic type of cellular automaton developed by Soares-Filho et al. (2002), which may be described as a spatio-temporal model for the analysis and simulation of land use changes.

Barredo and Gómez employ the MOLAND model, a cellular automata (CA) based model (White et al. 1999, Barredo et al. 2003 and 2004) that integrates various criteria in a probabilistic approximation to perform urban scenarios. In standard CA, the fundamental idea is that the state of a cell at any given time depends on the state of the cells within its neighbourhood in the previous time step, based on a set of transition rules. In the MOLAND model, a vector of transition potentials is calculated for each cell from the suitability, accessibility, zoning status and neighbourhood effect. Then, the obtained deterministic value is modified by the stochastic parameter using a modified extreme value distribution.

Aguilera et al. (modelling of greenhouse expansion), Valenzuela et al. (urban growth modelling) and Galtié (WUI fire risk modelling) implement a modelling method halfway between the use of existent modules and a self developed approach. The first two approaches, basically cellular automata, are implemented in the Macro Modeler of Idrisi Andes; the third one uses ArcGis software. Although they employ a software interface, the models of these authors are complex and specifically designed and therefore they have to be regarded as proper development as well.

Monteil et al. present a spatialised multi-agent model, the SMASH model (Spatialised Multi-Agent System for ASH colonisation), implemented using the CORMAS platform (Bousquet et al. 1999) and coupled to the vector data that were produced with ArcView software. SMASH illustrates a "companion modelling" approach for building a simulation model supporting analysis of prospective changes. It emphasises the role of reflexive character and the variety of individual behaviour of human participants on land-use change, which is currently regarded as an important feature to account for prospective studies (Greeuw et al. 2000). In the companion modelling approaches, the spatial multi-agent system (MAS) is developed in a participatory process.

With regard to Selleron and Mezzadri-Centeno, they compare a cellular automata and a fuzzy logic based model using specific algorithms developed in C++ by the authors themselves.

1.3.4 Data Bases: Raster or vector, origin and nature of variables

Most of the modelling issues presented below use databases in a raster format.

In the research of Monteil et al. the initialisation of the agent attributes is carried out by starting from the vector data layers, resulting from a geographical information system (GIS), developed on their study area with ArcView 3 software. This link between the vector representation in the GIS and the matrix representation in the spatialised multi-agent model thus requires a conversion between these two modes of representation (rasterisation of the vector layers). Procedures of import-export exist in the ArcView extension Spatial Analyst to rasterise a vector layer into a matrix of numerical values saved in the text format. Also CORMAS can import such files to initialise attributes of the cells.

Godoy and Soares-Filho also carried out a spatial data base, afterwards it was employed to realize a land use change analysis in the form of a transition matrix, first in vector format. The reasons are available data origin and data standardisation. This step is followed by data conversion because DINAMICA operates in a raster format. Guerrero et al. use vector representation of data as well in ArcView to perform a land use/land cover change analysis.

These examples illustrate that obviously many original data bases are in the vector format. All of them are then converted into images because every used model takes advantage of easier spatial analysis in grid cell format. The vector origin is related, on the one hand, to available official GIS data, provided by public administrations. On the other hand a lot of digitized maps come from aerial photo interpretation. Aerial photographs are the basic high scale data used to create a chronological land use/land cover set such as satellite images at lower scale. Vector digitalisation is also processed to extract information from existent analogical maps.

Regardless of the method of obtaining data, it is certain that raster data bases are closer to involved models. In this context, it has to be emphasised that digital ortho-photographs and especially satellite images – already in raster format – become more and more important. For the research of Selleron and Mezzadri-Centeno, Follador et al., Aguilera et al., Cuevas and Mas, Benito and Peñas, and Guerrero et al., remote sensing data with medium spatial resolution (mainly Landsat TM and ETM+, Spot and Aster but also Landsat MSS data for earlier dates) are the principal data sources to build a chronological series for model calibration. Also remote sensing data have a high temporal resolution, which permits the periodical retrieval of information for the same area. With this background, one notices the increasing use of available online images and maps; Google Earth, to name the most famous example is only one of a quickly growing number of websites. Aguilera et al. do so to update earlier ortho-photographs.

Barredo and Gómez use the datasets from the CORINE project (EEA 1993) as input data for their model thus the resulting scenarios have the same spatial and thematic properties as CORINE. Using this European-wide dataset makes it possible to model large European areas in a single implementation of the model.

Whatever the origin of land use/land cover maps is that form the principal modelled variable, it has to be mentioned that they are related to other variables, which are capable of explaining a more or less important part of land use/land cover variability in space and time. These explanatory variables sum up the 'knowledge' the model will use to compute a scenario or simulation. Generally, authors use distance and accessibility maps and DEM (digital elevation model) related maps such as topography, slope and aspect. Zoning status, like the one of protected areas or other territorial divisions, materializing management differences, bioclimatic information but also information about any form of human activity (economic, social, institutional, infrastructural) complete the large pool of involved data able to improve model outputs. To illustrate the huge spectrum of knowledge used to define variables, we quote here just the mobilised variables by Monteil et al. In order to simulate the interactions between land use options and ash encroachment for the long term (30 years), they take into account land cover (cropland, grassland, etc.), land use (crop, meadow, urban, etc.), slope (several classes) and identification numbers (farmer, cadastral parcel, and agricultural parcel). Agricultural parcels are the basic units of the farmers in the technical management of the farmland and farmers are the principal 'players'.

Among these explanatory variables authors often distinguish between those that will not significantly change during the training period and the simulation period (static variables like topography) and a second group of criteria changing rapidly (dynamic variables like accessibility). The difficulties, linked to different resolution/scales and information density, to combine all these data are so well known that we will not go into further detail here.

The techniques employed to measure the relationship between the explanatory variables and the variable to be modelled are various, but there are also various techniques to compute the helpful variables' weights of evidence.

Most of the authors employ traditional statistical tests like the Pearson correlation coefficient, a range of regression tests (linear, multiple, logistic), but also more recent tests about the goodness in terms of location like ROC statistics (Pontius and Batchu 2003) and various Kappa indexes (Pontius 2002). The free software DINAMICA includes a module for the definition of the categorisation intervals and automatic calculation of the weights of evidence. For each transition, it produces a transition probability map using the sum of the weights of evidence related to each category of the territorial configuration variable (Rodrigues et al. 2007). To do so, the entrance maps have to be spatially independent. As in other software, the Cramer's test and the measure of uncertainty of the combined information (Bonham-Carter 2002) is undertaken. Correlated variables have to be de-correlated or to be combined into a third one that will used by the model. The relationships calculated through the weights of evidence are applied to parameterise and to calibrate the simulation model.

Frequently, these data are used to aid in the creation of suitability maps for specific land use/land cover. Dependent on thematic model application, the same method also leads to vulnerability maps or risk maps. A lot of the research presented in this book (Aguilera et al., Camacho et al., Follador et al., Paegelow et al., Valenzuela et al.) employ the in Idrisi implemented multi-criteria evaluation (MCE) or GEOMOD (Benito and Peñas, Guerrero et al.).

1.3.5 Study areas and scales

The employed scale or the chosen spatial resolution and the fact that some contributions undertake a comparison between several study areas create another criterion to characterise the following case studies. Beginning with the last point, only two research studies compare two terrains in order to conceive more general conclusions. This is the case of Paegelow et al. applying the same models to two similar mountain areas in southern Europe. Also Galtié is basing his risk modelling approach on two different terrains in the south of France in order to include a representative sample of fire risk conditions of southwestern of Europe.

The spatial resolution (grid cell size) varies from 10 to 100 meters. Some authors also employ different resolutions and, consequently, nomenclatures. The finest grid (10 meters) is applied by Godoy and Soares-Filho. Grid resolutions of 20-25-30 meters are used by Camacho et al., Cuevas and Mas, Follador et al. and Paegelow et al. Selleron and Mezzadri-Centeno, after geometric correction and data homogenisation, finally use 75 meters raster cells. Aguilera et al., Barredo and Gómez, Benito and Peñas, Guerrero et al., and Valenzuela et al., chose spatial resolutions of about 50, 80 and 100 meters.

Monteil et al. try different rasterisation methods (information at pixel centre or use of the relative majority of the area) and various grid cell sizes (from 10 to 50 meters in pixel size) to convert the original vector data with the objective to simulate agricultural land use change at the parcel level under the conditions of a southern France mountain area. They, finally, adopt a resolution of about 14 meters.

Galtié deals with three scales (French department scale, municipality scale and infra-municipality scale) to take into account the different administrative, organisational forms of the territory, with their related fire prevention and fire-fighting services and objectives like identification of basins of risks and sensitive points. In this way, he mobilises hectometric, decametric and metric data in order to include hazard and stakes forming fire risk as well as to take into account fire dynamics at all scale levels.

The dimensions of study areas are also variable depending on the type of modelled environmental dynamics. The smallest areas are about 10-20 km^2: urban area of 8.5 km^2 (Godoy and Soares-Filho) corresponds to a quarter of Belo Horizonte (Brazil), rural area of 20 km^2 (Monteil et al.) in the Pyrenees mountain (France). Most of the terrains involved form local entities or little regions (from 200 to 2,000 km^2: Paegelow et al, Follador et al, Camacho et al., Selleron and Mezzadri-Centeno, Valenzuela et al., Aguilera et al., Cuevas and Mas) while Benito and Peñas work at the province level (Almería, Spain, 7,000 km^2). Barredo and Gómez employ the MOLAND model almost to the same extent (metropolitan area of Madrid, 8,000 km^2). Guerrero et al. use an entity constituted by four sub-regions in Michocán (Mexico) that covers 6,500 km^2. Galtié, dealing with two different areas, works from the local (0.01 km^2) to the regional (2-400 km^2) and zonal (400 km^2) scales.

1.3.6 Calibration, results and validation techniques

An important aspect in all the case studies is the calibration and validation of computed results. Consequently, we also focus in this presentation on these aspects that are essential in order to contribute to developing modelling tools for environmental dynamics applicable in current management and forecast tasks.

1.3.6.1 Calibration

The calibration of performed models usually requires a training period including a chronological series of maps about the environmental dynamic to be modelled and the explanatory variables. With regard to the number of maps or images forming the training data base used to calibrate the model, a majority of the research presented here are based on two dates and the dynamics during this selected period. In other words, the performed temporal simulation – almost always undertaken by way of conditional probabilistic transition matrices – is carried out with two dates to model a posterior third date. This is evidently a difficult situation for researchers, who wish to deal with numerous training dates depending on the modelled object but often reflects the reality in terms of available data or time to elaborate them.

Some authors, like Selleron and Mezzadri-Centeno, call on three dates for the model calibration. Modelling approaches by neural networks and polychotomous regression (Paegelow et al.) mobilise all available training data for model configuration. Then the model calibration is done stepwise, from one date to the next.

The optimisation model by multi-criteria evaluation, used by Camacho et al., makes use of one calibration date, the oldest one, to process retrospective modelling.

Aguilera et al. and also Valenzuela et al. propose models that are based on one date as a reference state to simulate a later one. In these studies, the authors consider the concept of calibration as an adjustment process for the model to be as similar as possible to reality. For example, Aguilera et al. consider the calibration as a model configuration process that allows for the creation of an ex post simulation for actual conditions using known information. So they calibrate their model by generating various simulations for today and then compare them with reality. However this 'trial and error' method is quite common during the calibration step with the aim to optimise and configure the model.

The calibration of the risk models proposed by Galtié operates on two levels: at the overall model level, using a method based on experts' statements; at intrinsic aggregate model level, using a method based on crossing experts' statements, existent models, in situ observations and experimental validations.

Monteil et al., building a participatory multi-agent system model, use knowledge of local players and scientists based upon the recent past in order to calibrate the rules involved in the model.

Coming back to the most typical scenario, the length of the training period depends on the one hand, on the considered dynamic and its swiftness, and on the other hand on the time span of macro-system conditions that can be simulated for the near future. The span of calibration time varies from steps of two to three years (Cuevas and Mas, Follador et al.) to about a decade (French study area in Paegelow et al., Selleron and Mezzadri-Centeno, Barredo and Gómez, Benito and Peñas, Godoy and Soares-Filho, Guerrero et al.) to a phase closer to twenty or thirty years (Spanish study area in Paegelow et al.) and even fifty years (Monteil et al.).

A related issue is the time step between the last calibration date and the validation date although, once again, presented studies differ in length and significance. A lot of models are applied accordingly so that the simulation date corresponds to the last available (model unknown) date in order to perform a comparison with reality in terms of the goodness of the prediction and specific misclassification. The number of years separating the last model known calibration date and the date of simulation is about three to five years, respectively (Cuevas and Mas, Follador et al., Selleron and Mezzadri-Centeno) and eleven to fourteen years (Paegelow according to the two study areas). The time step is about fifteen and seventeen years for both Aguilera et al. and Valenzuela et al. using the simulation for calibration as well as for validation.

In the second group of elaborated models one of the simulations corresponds to the known model's last/actual reality map. In other words, one of the model outputs (mainly as a validation step to perform long term simulation scenarios) is useful for its validation (Godoy and Soares-Filho, Benito and Peñas, Barredo and Gómez).

1.3.6.2 Results

Most of the following case studies carry out a model output in the form of simulation maps or mapped scenarios either corresponding to the last available real situation or to the near future, with the exception of the retrospective modelling of Camacho et al. Some authors perform various scenarios depending on different dynamics or anticipating a range of possible changing (Monteil et al., Godoy and Soares-Filho).

The future projections are achieved in the following studies: Selleron and Mezzadri-Centeno (projections to 2000, 2005 and 2010), Aguilera et al. (2025), Valenzuela et al. (2018), Benito and Peñas (2010), Barredo and Gómez (2040), Godoy and Soares-Filho (2012 and 2020), Cuevas and Mas (2015), Guerrero et al. (2025). As mentioned above some of them present multiple scenarios. Aguilera et al. carry out three future simulations about greenhouse growth: stabilization, tendency growth reflecting the trajectory of the recent past, and moderate growth. Benito and Peñas also compute three scenarios about greenhouse growth and their ecological and environmental effects: linear, accelerated and slowed growth. Developing models for urban growth, Barredo and Gómez propose three simulations differing particularly in spatial location: scattered growth, rapid urban growth, compact development, from scenarios produced by the Intergovernmental Panel on Climate Change (IPCC) in the Special Report on

Emissions Scenarios (SRES). Valenzuela et al., involved in urban dynamics and urbanisation patterns, compute four scenarios varying spatially in urban patterns: aggregated, lineal, junction growth and growth in the form of planned residential barriers. Cuevas and Mas, computing a participatory land use modelling tool, show first the trend scenario following the amount and pattern observed during the training period. Alternatively, they develop a 'cattle' scenario that presumes a loss of social cohesion and an increased conversion of dry tropical forest to pastures for cattle, but also a sustainable scenario supposing implementation of protected areas and the promotion of sustainable pastoralism.

Camacho et al. calculate retrospective simulations corresponding to three dates (1571, 1752 and 1851) for which statistical data about land use are available. The computed probabilistic spatial distribution of land use can not be validated at the infra-municipality level and only the comparison with the closest land use map corresponding to the middle of the 20th century permits any conclusions about the goodness of fit.

Galtié, contributing to archive for an operational fire risk model, calculates various scale dependant risk indicators for long time periods (risk prevention) as well as for immediate time periods (operational prevision).

Monteil et al. are building a multi-agent model simulating ecological processes of ash colonisation and farmers' land management behaviour to explore scenarios of change in agricultural land use and landscape reforestation and their social and environmental consequences according to the impact of assumed changes in the socio-economical environment (public policies for agriculture; rural urbanisation) on farmer's behaviour. Preferring a participatory approach, the construction and calibration of the farmers' behaviour model are the principal results. Scenarios are still on-going and a set of visualisations (interactive maps, plots of selected indicators of the farmland and the landscape levels, dynamic crosstabs of operations and land use/land cover changes) are being worked out to support the participatory assessment.

1.3.6.3 Validation techniques

Some authors first process a visual comparison between real and simulated land use/land cover maps (Aguilera et al., Barredo and Gómez, Follador et al., Paegelow et al., Selleron and Mezzadri-Centeno). Then they use, like most of the researchers, statistical tests to quantify the prediction score in terms of the correct extent and spatial localisation. Although some model outputs are difficult to validate by these methods (e.g., fire risk or long term scenarios) and authors have recourse to expert opinion. Among the variety of statistical tools that authors apply to compare either real to simulated results or simulations with each other we have listed the following popular methods.

- Cumulated surface by category (which doesn't care about correct localisation);
- Pixel-by-pixel validation using matrices (simple to process but doesn't consider the agreement of spatial proximity);
- Correct prediction scores and residues;
- Various Kappa indices (Pontius 2002) measuring the agreement in terms of quantity and quality (location);
- LUCC (Land Use/Land Cover Change) budget focussing only on the changes (Pontius et al. 2004) and it is more difficult to predict changes than stability;
- Fuzzy logic based indices (Hagen 2003, Hagen-Zanker et al. 2005) measuring the agreement of location and overcoming the restrictions induced by hard pixel limits like pattern quantification and exclusive cell state.

To this basic list of validation instruments, some authors add more specific tools, which are needed either for a singular thematic or available by specific software. Accordingly, Benito and Peñas are measuring the spatial similarity of model outputs (greenhouse growth) by Procrustes analysis (Jackson 1995). It compares the fit between different matrices (e.g., real and modelled distribution) by linear transformation (rotation, translation, scaling) of one grid to achieve the best fit with the reference grid. The index of agreement is the sum of squared errors; the lower it is the better is the agreement.

DINAMICA EGO, employed by Cuevas and Mas, Follador et al. and Godoy and Soares-Filho offers a special, fuzzy logic based, tool measuring what we called agreement of quality or spatial similarity. Referring also to the research of Hagen (2003), DINAMICA EGO provides a vicinity-based comparison tool measuring the fuzzyness of location (Rodrigues et al. 2007).

Another way to quantify spatial similarity consists of applying ecological indices (refer to McGarigal and Marks 1995 and Botequilha et al. 2006 for an exhaustive description of these metrics) like patch number or medium patch size. Aguilera et al. also uses this as well.

Galtié implements and compares three methods of validation/calibration: crossing of produced risk values and historical and current fire occurrences, comparative analysis of results derived from existing methods and validation by experts' statements.

Monteil et al. provide their companion model based on a multi-agent system with some visualization features to facilitate validation of the conceptual model with local partners and experts (conceptual validity in the meaning of Rykiel 1996: ensuring that assumptions underlying the conceptual model are correct or justifiable and that the representation of the system in the model is reasonable for the model's intended use).

1.3.7 Outcome and originality

The previously developed criteria are helpful to characterise the following contributions but are insufficient to give an entire comprehensive view of them and to classify them. Therefore we index the following research examples with regard to their originality and their outcome. These are the aspects that emphasise the best of the scientific and methodological contribution of each work and may be their best study to date. As a result we group the thirteen articles into five chapters.

They are only a sample of the variety of methodological approaches, and thematic applications for environmental dynamics and objectives for simulation. Most of them are at the crossroads for these criteria and this makes it difficult to clearly order them in accordance with fundamental notions like the nature of the model, the modelled variable or the principal aim that motivates the research. However, some proximities or associations clearly appear and allow the ordering of the selected examples into some sets.

- *Model comparison applied to deforestation and reforestation*

  A first series of four articles deals with deforestation (in Central and South America) while European mountains are characterised by an important spontaneous reforestation. The first article clearly has a thematic objective: reducing carbon emission related to tropical deforestation while the three following tend towards methodological comparison and model validation.
- *Decision support and participatory modelling*

  Decision support as a practical application of geomatics evidently tends to offer innovative tools to assist environmental management. The first article of this set deals with fire risk to improve risk prevention while the two other's on top of that explore the participatory approach in modelling often related to the concept of sustainable development.
- *Retrospective modelling*

  Contrary to all other examples, the authors here explore a multi-criteria approach applied to model historical land use.
- *Multi objective conflicts and environmental impact of intensive agriculture*

  Leaning on the example of greenhouse expanding on the Andalusian coast, the authors focus on two more general problems: the concurrence between different land uses on a limited space and the environmental impact of this form of development.

- *Urban environment and urban growth*

Finally, three articles illustrate environmental problems in urban space and urban growth related to land use conflicts. Two contributions are applying different models to simulate urban land use change while the third is exploring land use scenarios in urban regions related to climate change scenarios.

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References

Aspinall RJ, Pearson DM (1996) Data quality and spatial analysis: analytical use of GIS for ecological modeling. In: Goodchild MF, Steyaert LT, Parks BO (eds) GIS and Environmental modeling: progress and research issues. Fort Collins, CO, GIS World Books

Atkinson PM, Martin D (eds) (2000) Innovations in GIS VII. Gis and geocomputation. London, Taylor & Francis

Balzter H (2000) Markov chain modelling for vegetation dynamics. Ecological Modelling, 126 (2-3), pp 139-154

Barredo JI, Kasanko M, McCormick N, Lavalle C (2003) Modelling dynamic spatial processes: simulation of urban future scenarios through cellular automata. Landscape and Urban Planning 64, pp 145-160

Barredo JI, Demicheli L, Lavalle C, Kasanko M, McCormick N (2004) Modelling future urban scenarios in developing countries: an application case study in Lagos, Nigeria. Environment and Planning B: Planning and Design 32, pp 65-84

Bascompte J, Sole RV (eds) (1998) Modeling Spatiotemporal Dynamics in Ecology. Springer, Berlin Heidelberg New York

Batty M (1976) Urban Modeling: Algorithms, Calibrations, Predictions. Cambridge, Cambridge University Press

Batty M (2003) New Developments in Urban Modeling: Simulation, Representation, and Visualization. In: Guhathakurta S (ed) Integrated Land Use and Environmental Models: A Survey of Current Applications and Research. Springer, Berlin Heidelberg New York

Batty M, Xie Y (1999) Modelling Urban Dynamics through GIS-based Cellular Automata. Computers, Environment and Urban Systems 23 (3), pp 205-233

Benenson I, Torrens PM (2004) Geosimulation: automata-based modelling of urban phenomena. Hoboken, NJ, John Wiley & Sons

Bishop CM (1995) Neural Networks for pattern recognition. New York, Oxford University Press, 482 pp

Bonham-Carter GF (2002) Geographic information systems for geoscientists: modelling with GIS. Ottawa, Pergamon

Botequilha A, Miller J, Ahern J, McGarigal K (2006) Measuring Landscapes. A planner´s handbook. Washington, Island Press

Bouchon-Meunier B (1995) La logique floue et ses applications. Paris, Addison-Wesley, 257 pp

Bousquet F, Gautier D (1999) Comparaison de deux approches de modélisation des dynamiques spatiales par simulation multi-agents: Les approches «Spatiale» et «Acteurs». Cybergeo 89, 13 avril, 12 pp http://www.cybergeo.presse.fr/

Bouzeghoub M, Gardain G, Valduriez P (2000) Les objets. Paris, Eyrolles, 450 pp

Bregt AK, Skidmore AK, Nieuwenhuis G (2002) Environmental modeling: issues and discussion. In: Skidmore A (ed) Environmental modelling with GIS and remote sensing. London, Taylor and Francis

Briassoulis H (2000) Analysis of land Use Change: Theoretical and Modelling Approaches. Regional Research Institute, West Virginia University, Web Book: http://www.rri.wvu.edu/WebBook/Briassoulis/contents.htm

Brimicombe A (2003) GIS, Environmental Modelling and Engineering. Taylor and Francis

Briot JP, Demazeau Y (2001) Principes et architecture des sytèmes multi-agents (Traité IC2, Informatique et systèmes d'information). Hermès Lavoisier, 268 pp

Burks AW (1970) Essays on Cellular Automata. University of Illinois Press, 375 pp

Burrough P (1986) Principles of Geographical Information Systems for Land Resources Assessment. Oxford, Oxford Science

Burrough PA, McDonnell R (1998) Principles of Geographical Information Systems Spatial Information Systems and Geostatistics. Oxford, Oxford University Press

Buzai GD (2006) Geografía y Sistemas de Información Geográfica. In: Hiernaux D, Lindón A (eds) Tratado de Geografía Humana. Editorial Anthropos, Universidad Autónoma Metropolitana

Campagna M (ed) (2005) GIS for Sustainable Development. Taylor & Francis CRC Press

Castella JC, Ngoc Trung T, Boissau S (2005) Participatory simulation of land-use changes in the northern mountains of Vietnam: the combined use of an agent-based model, a role-playing game, and a geographic information system. Ecology and Society, 101, pp 1-27

Centeno TM, Góis JA (2005) Integrating fuzzy images and heterogeneous data to support the ambiental impact forecast. Proceedings of XII Simpósio Brasileiro de Sensoriamento Remoto, pp 3037-3044

Centeno TM, Saint-Joan D, Desachy J (2006) Approach of the spatio-temporal prediction using vectorial geographic data. Proceedings of SPIE, Remote Sensing for Geography, Geology, Land Planning and Cultural Heritage, 2960, pp 96-103, Italy

Cheylan JP, Lardon S, Mathian H, Sanders L (1994) Les problématiques de l'espace et le temps dans les sig. Revue de Géomatique 4 (3-4), pp 287-305

Christakos G, Bogaert P, Serre ML (2001) Temporal GIS: Advanced Functions for Field-Based Applications. Springer, Berlin Heidelberg New York

Chuvieco Salinero E (1993) Integration of Linear Programming and GIS for Land-use Modeling. International Journal of Geographical Information Systems 7, no 1 (1993), pp 71-83

Chuvieco Salinero E (2006) Teledetección Ambiental. La observación de la tierra desde el espacio. Ariel Ciencia, 2ª ed, Barcelona

Chuvieco Salinero E (ed) (2008) Earth Observation of Global Change. The Role of Satellite Remote Sensing in Monitoring the Global Environment. Springer, Berlin Heidelberg New York

Claramunt C (1994) Sémantique et logique spatio-temporelles. Revue Internationale de Géomatique 4, pp 165-180

ComMod C (2005) La modélisation comme outil d'accompagnement. Nature Sciences Sociétés 13, pp 165-168

Costanza R, Voinov A (eds) (2004) Landscape Simulation Modeling. A Spatially Explicit, Dynamic Approach. Springer, Berlin Heidelberg New York

Coquillard P, Hill DRC (1997) Modélisation et simulation d'écosystèmes. Des modèles déterministes aux simulations à événements discrets. Paris, Masson

Crane MP, Goodchild MF (1993) Epilog. In: Goodchild MF, Parks BO and Steyart LT (eds) Environmental modeling with GIS. New York, Oxford University Press

Crosetto M, Tarantola S (2001) Uncernainty and sensitivity analysis tools for GIS-based model implementation. International Journal of Geographical Information Science 15 (5), pp 415-437

Crosetto M, Tarantola S, Saltelli A (2000) Sensitivity and uncernainty analysis in spatial modeling based on GIS. Agriculture, Ecosystems and Environment 81 (1), pp 71-79

Croswell PL, Clark SR (1988) Trends in automated mapping and geographic system hardware. Photogrammetric Engineering and Remote Sensing 54, pp 1571-1576

Davalo E, Naim P (1969) Des réseaux de neurones. Paris, Eyrolles, 232 pp

DeMers MN (2002) GIS modeling in raster. New York, Wiley

Dietzel C, Oguz H, Hemphill JJ, Clarke KC, Gazulis N (2005) Diffusion and coalescence of the Houston Metropolitan Area: evidence supporting a new urban theory. Environment and Planning-B, Planning and Design 32, no 2, pp 231-236

Dragicevic S, Marceau DJ (2000) A fuzzy logic approach for modeling time in GIS. International Journal of Geographic Information Science 14 (3), pp 225-245

Dubé P, Fortin MJ, Canham C, Marceau DJ (2001) Quantifying global gap dynamics and spatio-temporal structures in spatially explicit models of temperate forest ecosystems. Ecological Modelling 142 (1-2), pp 39-60

Eastman JR (1993) IDRISI, A grid based geographic analysis system, Version 41. Massachusetts, Clark University

Eastman JR (2001) The evolution of Modeling Tools in GIS. Directions Magazine. http//wwwdirectionsmagcom

Eastman JR (2006) Idrisi Andes Tutorial. Clark Labs, Worcester, MA

Eastman JR, McKendry J (1991) Change and Time Series Analysis in GIS. UNITAR

Eastman JR, Kyrem PAK, Toledano J, Jin W (1993) A procedure for Multi-Objective Decision Marking in GIS under conditions of Competing Objectives. Proceedings of EGIS'93, pp 438-447

EEA (1993) CORINE Land Cover - Technical Guide. Luxembourg: Office for Official Publications of European Communities

Egenhofer MJ, Golledge RG (1994) Time in geographic space: Report of the specialist meeting of research initiative 10. Technical report 94-9, NCGIA

Elmozino H, Lobry C (1997) Automates cellulaires et modélisation de la dynamique forestière. Ecologie 28 (4), pp 307-324

Emshoff JR, Sisson RL (1970) Design and use of computer simulation models. Mac Millan, Londres

Engelen G (2003) References Cellular Automata – LUCMOD (land use change modelling). LUCC website, International Project Office, Louvain-La-Neuve, Belgium http//www.geo.ucl.ac.be/LUCC/MODLUC_Course/Presentations/Guy_engelen/CA-References.doc

EUR-JRC (2004) The MOLAND model for urban and regional growth forecast. A tool for the definition of sustainable development paths. Technical Report EUR21480 http//moland.jrc.it/documents/EUR_21480_2004_Moland_model.pdf

Ferrand N (1997) Modèles multi-agents pour l'aide à la décision et la négociation en aménagement du territoire. Thesis, University Joseph Fourier, Grenoble, 305 pp

Fischer M, Nijkamp P (eds) (1993) Geographic information systems, spatial modelling and policy evaluation. Berlin, Springer-Verlag

Flamm RO, Turner MG (1994) Alternative model formulations for stochastic simulation of landscape change. Landscape Ecology 9(1), pp 37-44

Forman RTT (1995) Land Mosaics: The Ecology of Landscapes and Regions. Cambridge EEUU

Forrester JW (1969) Urban dynamics. Cambridge, Massachusetts, MIT Press, 285 pp

Fotheringham AS, Wegener M (2000) Spatial models and GIS. New potencial and new models. London, Taylor and Francis

Franc A, Sanders L (1998) Modèles et systèmes multi-agents en écologie et en géographie: état de l'art et comparaison avec les approches classiques. In: Ferrand N (ed) Modèles et systèmes multi-agents pour la gestion de l'environnement et des territoires. Clermont-Ferrand, SMAGET

Frihida A, Marceau DJ, Thériault M (2002) Spatio-temporal object-oriented data model for disaggregate travel behaviour. Transactions in GIS 6 (3), pp 277-294

Gardner M (1970) The Fantastic Combinations of John Conway's New Solitaire Game 'Life'. Scientific American 23, 4, pp 120-123

Gardner M (1971) On cellular automata, self-reproduction, the Garden of Eden and the game of the life. Scientific American 224, pp 112-117

Giacomeli A (2005) Integration of GIS and Simulation Models. In: Campagna M (ed) GIS for Sustainable Development. Taylor & Francis CRC Press

Giarratano JC, Rilay GD (2005) Expert systems. Principles and programming. PWS Publishing Company, Boston, 585 pp

Gómez Delgado M, Barredo JI (2005) Sistemas de Información Geográfica y evaluación multicriterio en la ordenación del territorio (GIS and multicriteria evaluation for urban and regional planning). Ra-Ma, Madrid

Gómez Delgado M, Tarantola S (2006) Global sensitivity analysis, GIS and multi-criteria evaluation for a sustainable planning of hazardous waste disposal site in Spain. International Journal of Geographical Information Science 20, pp 449-466

Goodchild MF, Parks BO, Steyaert LT (1993) Environmental modeling with GIS. New York, Oxford University Press

Goodchild MF, Steyaert LT, Parks BO (1996) GIS and Environmental modeling progress and research issues. Fort Collins, CO GIS World Books

Greeuw SCH, Van Asselt MBA, Grosskurth MBA, Storms CAMH, Rijkens-Klomp N, Rothman DS, Rotsmans J (2000) Cloudy crystal balls. An assessment of recent European and global scenarios studies and model. International Centre for Integrative Studies (ICIS) for EEA, Copenhagen, Denmark, n°17, 112 pp

Guhathakurta S (ed) (2003) Integrated Land Use and Environmental Models: A Survey of Current Applications and Research. Springer, Berlin

Hagen A (2003) Fuzzy set approach to assessing similarity of categorical maps. International Journal of Geographical Information Science 17(3), pp 235–249

Hanley JA, McNeil BJ (1982) The meaning and use of the area under a receiver operating characteristic (ROC) curve. Radiology 143, pp 29-36

Hathout S (2002) The use of GIS for monitoring and predicting urban growth in East and West St Paul. Winnipeg, Manitoba, Canada Journal of Environmental Management 66, pp 229-238

Hebb D (1949) The Organization of Behavior. New York, Wiley, 335 pp

Heuvelink GBM (1998) Error propagation in environmental modeling with GIS. London, Taylor and Francis

Hill DRC (1993) Analyse orientée objet et modélisation par simulation. Addison-Wesley

Huston MA, Angelis De DL (1994) Competition and coexistence the effects of ressources transport and supply rates. The American Naturalist 144 (6), pp 954-977

Isachenko GrA, Reznikov AI (1995) Landscape-dynamical scenarios simulation and mapping in geographic information systems. 17th Inter Cartographic Conference, Sept 3-9, 1995 Proceedings 1 Barcelona, pp 800-804

Issaev B, Nijkamp P, Rietveld P, Snickars F (eds) (1982) Multiregional Economic Modeling. Amsterdam North-Holland

Jacewicz P (2002) Modélisation et simulation distribuées par automates cellulaires. Application en écologie. Thesis, University of Perpignan, 147 pp

James W (1890) Association. In: Psychology (Briefer Course). New York, Holt, pp 253-279

Jen E (1990) A periodicity in One-dimensional Cellular Automata. Physica D 45, pp 3-18

Kanevski M, Maignan M (2004) Analysis and modelling of spatial environmental data. EPEL Press, 288 pp

Kuhlman T, Tabeau A, Gaaff A, Tongeren F van, Dekkers JEC (2005) Linking models in land use simulation. Application of the Land Use Scanner to changes in agricultural area. Proceedings of the 45th congress of the European Regional Science Association, Amsterdam, the Netherlands, August 23-27, 2005, URL http//wwwlumosinfo/resources/File/1_kuhlman2005pdf

Lai TL, Wong S (2001) Stochastic Neural Networks with Applications to Nonlinear Time Series. Journal of the American Statistical Association 96 (455), pp 968-981

Lambin EF, Geist HJ (eds) (2006) Land-Use and Land-Cover Change Local processes and global impacts. Springer-Verlag, Berlin Heidelberg

Langlois A, Philipps M (1997) Automates cellulaires. Paris, Hermès, 197 pp

Langran G (1992) Time in Geographic Information Systems. Taylor and Francis, Londres

Langran G (1993) Issues of implementing a spatiotemporal system. International Journal of Geographical Information Systems 7, pp 25-43

Lardon S, Cheylan JP, Libourel T (1997) Le temps dans les sig: dynamique des entités spatio-temporelles. In: Les temps de l'environnement. Les Journées du PIREVS, Toulouse 5-7 novembre, pp 147-152

Laurini R, Thompson D (1992) Fundamentals of spatial information systems. San Diego, Academic Press, 640 pp

Le Berre M, Brocard M (1997) Modélisation et espace. In: Espaces, territoires et sociétés. Les recherches françaises en perspective. Colloque de la section 39 du Comité National de la Recherche Scientifique, Paris, CNRS, pp 23-30

Lee R ST (2004) Fuzzy-Neuro Approach to Agent Applications. From the AI Perspective to Modern Ontology. Heidelberg, Springer-Verlag, 350 pp

Lippe E, Smidt De JT, Glenn-Lewin DC (1985) Markov models and succession a test from a heathland in the Netherlands. Journal of Ecology 73, pp 775-791

Logofet D, Lesnaya E (2000) The mathematics of Markov models: what Markov chains can really predict in forest succession. Ecological Modelling 125 (2-3), pp 258-298

Longley PA, Batty M (1996) Spatial Analysis: Modelling in a GIS Environment. Wiley, New York

Longley PA, Batty, M (eds) (2003) Advanced spatial analysis: the CASA book of GIS. Redlands, ESRI Press

Longley PA, Goodchild MF, Maguire DJ, Rhind DW (1999) Geographical Information Systems. Wiley, New York

Longley PA, Goodchild MF, Maguire DJ, Rhind DW (2001) Geographic Information Systems and Science. Wiley, Chichester

Longley PA, de Smith M, Goodchild M (2007) Geospatial Analysis – A comprehensive Guide to Principles, Techniques and Software Tools. Matador, Leicester

López E, Bocco G, Mendoza M, Duhau E (2001) Predicting land-cover and land-use change in the urban fringe – A case of Morelia city, Mexico. Landscape and Urban Planning 55, pp 271-285

Maguire DJ (1989) Computers in Geography. Longman Group, New York

McGarigal K, Marks BJ (1995) FRAGSTATS: Spatial pattern analysis program for Quantifying Landscape Structure. USDA For. Serv. Gen. Tech. Rep. PNW-351

Malczewski J (1999) GIS and multicriteria decisión analysis. New York, John Wiley & Sons

Martín B, Sanz A (2006) Redes neuronales y sistemas borrosos. Edit Ra-Ma, 442 pp

Metropolis N, Ulam S (1949) The Monte Carlo method. Journal of the American Statistical Association 44, pp 335-341

Mezzadri-Centeno T (1998) La modélisation et la projection spatio-temporelle dans les SIG. Thesis, University Paul Sabatier, Toulouse, 140 pp

Minsky ML (1965) Matter, minds and models. International Federation of Information Processing Congress 1, pp 45-49

Minsky ML (1987) Society and mind. New York, Simon and Schuster, 339 pp

Mladenoff DJ, Baker WL (eds) (1999) Spatial modeling of forest landscape change: approaches and applications. Cambridge, Cambridge University Press

Molenaar M (1998) An Introduction to the theory of spatial object modelling for GIS. London, Taylor & Francis

Neumann Von J (1966) Theory of Self-Reproducing Automata. University of Illinois Press

Nunes C, Augé JI (eds) (1999) IGBP Report n° 48 and IHDP Report n° 10. Land-Use and Land-Cover Change (LUCC). Implementation Strategy. http//www.geo.ucl.ac.be/LUCC/lucc.html

Odum HT (1957) Trophic structure and productivity of Silver Springs, Florida. Ecological Monographs 22, pp 55-212

Openshaw S, Abrahart RJ (eds) (2000) Geocomputation. London, Taylor and Francis

Ott T, Swiaczny F (2001) Time-integrative geographic information systems management and analysis of spatio-temporal data. Berlin [etc] Springer

Paque D (2004) Gestion de l'historicité et méthodes de mise à jour dans les SIG. Cybergéo 278, 6 pp

Parker DC, Berger T, Manson SM (eds) (2001) LUCC Report Series N° 6: Agent-Based Models of Land-Use and Land Cover Change (ABM/LUCC). Report and Review of an International Workshop. Irvine, Califonia, USA, 4-7 octobre, 140 pp http//www.indiana.edu/~act/focus1/ABM_Report6.pdf

Parker DC, Manson SM, Janssen MA, Hoffman MJ, Deadman P (2003) Multi-Agent Systems for the Simulation of Land-Use and Land-Cover Change: A Review. Annals of the Association of American Geographers 93:2, pp 314-337

Parlitz U, Merkwirth C (2000) Nonlinear prediction of spatio-temporal time series. ESANN'2000 Proceedings, Bruges, pp 317-322

Petry FE, Robinson VB, Cobb MA (eds) (2005) Fuzzy modeling with spatial information for geographic problems. New York, NY Springer

Phillips SJ, Anderson RP, Schapire RE (2006) Maximum entropy modeling of species geographic distributions. Ecological Modelling 190, pp 231-259

Poix C, Michelin Y (2000) Simulation paysagère : un modèle multi-agents pour prendre en compte les relations sociales. Cybergeo 116, 11 pp http//www.cybergeo.presse.fr/

Pontius RG Jr (2002) Statistical methods to partition effects of quantity and location during comparison of categorical maps at multiple resolutions. Photogrammetric Engineering & Remote Sensing 68(10), pp 1041-1049
Pontius RG Jr, Batchu, K (2003) Using the Relative Operating Characteristic to Quantify Certainty in Prediction of Location of Land Cover Change in India. Transactions in GIS 7(4), pp 467–484
Pontius RG Jr, Chen H (2006) Land Use and Cover Change Modelling. Land Change Modeling with GEOMOD, Idrisi Andes Tutorial, Clark University
Pontius RG Jr, Schneider LC (2001) Land-cover change model validation by an ROC method for the Ipswich watershed. Massachusetts, USA, Agriculture, Ecosystems & Environment 85, pp 239–248
Pontius RG Jr, Cornell JD, Hall CAS (2001) Modeling the spatial pattern of land-use change with GEOMOD2: application and validation for Costa Rica. Agriculture Ecosystems & Environment 85, pp 191-203
Pontius RG Jr, Shusas E, McEachern M (2004) Detecting important categorical land changes while accounting for persistence. Agriculture, Ecosystems & Environment 101, pp 251–268
Quattrochi DA, Goodchild MF (1997) Scale in Remote Sensing and GIS. Boca Raton, Florida, CRC press, 406 pp
Reginster I, Rounsevell M (2006) Scenarios of future urban land use in Europe. Environment and Planning B: Planning and Design 33, pp 619-636
Rodrigues HO, Soares Filho BS, de Souza Costa WL (2007) Dinamica EGO, uma plataforma para modelagem de sistemas ambientais. Anais XIII Simposio Brasileiro de Sensoriamento Remoto, INPE, pp 3089-3096
Rodríguez-Bachiller A, Glasson J (2004) Expert systems and geographical information systems for impact assessment. London, Taylor & Francis
Roman J (2004) Algorithmique parallèle et simulation haute performance appliquées à la dynamique de populations de parasites. Scientific report 2000-2003 from M3PEC, DRIMM, University Bordeaux 1, http://www.m3pec.u-bordeaux1.fr/roman2.pdf
Rosenblatt F (1958) The Perceptron: a probabilistic model for information storage and organization in the brain. Psychological Review 65, pp 386-408
Ruas A (1999) Modèle de généralisation de données urbaines à base de contraintes et d'autonomie. Cybergéo 107, 14 pp, http//www.cybergeo.presse.fr/
Ruas A (ed) (2002) Généralisation et représentation multiple. Hermès science, 390 pp
Rykiel EJJ (1996) Testing ecological models: the meaning of validation. Ecological Modelling 90, pp 229-244
Saint-Joan D, Desachy J (1995) A Fuzzy Expert System for Geographical problems: an agricultural application. Proceedings of the IEEE International Conference on Fuzzy Systems - FUZZ-IEEE'1995, 2, pp 469-476
Savall M, Pécuchet JP, Chaignaud N, Itmi M (2001) YAMAM – un modèle ‘organisation pour les systèmes multi-agents. Implémentation dans la plate-forme Phœnix. Proceedings of 3ème Conférence Francophone MOSIM (Modélisation et simulation), 25-27 août, Troyes, France

Schultz REO, Centeno TM, Delgado MRBS (2006) Spatio-temporal prediction by means of a fuzzy rule-based approach. Proceedings of the IEEE International Conference on Fuzzy Systems - FUZZ-IEEE'2006, pp 6621-6628

SCS (Society for Computer Simulation) (1979) Technical Comitee on Model Credibility, Terminology for Model Credibility. Simulation 32 (3), pp 103-107

Singh RB, Fox J, Himiyama Y (2001) Land use and cover change. Enfield, NH, Science Publishers

Skidmore A (ed) (2002) Environmental modelling with GIS and remote sensing. London, Taylor and Francis

Soares Filho BS, Pennachin CL, Cerqueira G (2002) DINAMICA – a stochastic cellular automata model designed to simulate the landscape dynamics in an Amazonian colonization frontier. Ecological Modelling 154, pp 217-235

Soares Filho BS, Nepstad D, Curran L, Voll E, Cerqueira G, Garcia RA, Ramos CA, Mcdonald A, Lefebvre P, Schlesinger P (2006) Modeling conservation in the Amazon basin. Nature, London, 440, pp 520-523

Spearman C (1904) General intelligence objectively determinated and measured. American Journal of Psychology 15, pp 201-293

Stahl K (1986) Theories of Urban Business Location. In: Handbook of Regional and Urban Economics, vol 2, ES Mills, pp 759 -820, Amsterdam, North-Holland

Stillwell J, Clarke G (eds) (2004) Applied GIS and spatial analysis. Chichester, John Wiley and Sons

Tate NJ, Atkinson PM (2001) Modelling scale in Geographical Information Science. John Wiley and Sons

Tilman D (1977) Resource competition between planktonic algae: an experimental and theoretical approach. Ecology 58, pp 338-348

Tong-Tong JR (1995) La logique floue. Hermès, 160 pp

Tosic P, Agha G (2003) Understanding and Modeling Agent Autonomy in Dynamic Multi-Agent, Multi-Task Environments. Proc First European Workshop on Multi-Agent Systems (EUMAS '03), Oxford, UK, 18-19 December

Tosic P, Agha G (2004a) Concurrency vs Sequential Interleavings in 1-D Threshold Cellular Automata. Proc IEEE - IPDPS '04 (APDCM Workshop), Santa Fe, New Mexico, USA, 26-30 April

Tosic P, Agha G (2004b) Towards a Hierarchical Taxonomy of Autonomous Agents. Proc IEEE Int'l Conference on Systems, Man and Cybernetics (IEEE-SMC'04), The Hague, Netherlands, 10-13 October

Tobler WR (1979) Cellular Geography. In: Gale S, Olsson G (eds) Philosophy in Geography Kluwer, pp 379-386

Tucker BC, Arnand M (2004) The Application of Markov Models in Recovery and restoration. International Journal of Ecological Environmental Sciences 30, pp 131-140

Turing A (1950) Computer machinery and intelligence. Mind 49, pp 433-460

Verburg PH, Soepboer W, Veldkamp A, Limpiada R, Espaldon V, Sharifah Mastura SA (2002) Modeling the Spatial Dynamics of Regional Land Use the CLUE-S Model. Environmental Management, vol 30(3), pp 391-405

Verburg PH, Kasper K, Pontius RG Jr and Veldkamp A (2006a) Modelling land use and land cover change. In: Lambin EF, Geist HJ (eds) Land-Use and Land-Cover Change: Local processes and global impacts, pp 117-135, Heidelberg Springer-Verlag Berlin

Verburg PH, Schulp CJE, Witte N, Veldkamp A (2006b) Downscaling of land use change scenarios to assess the dynamics of European landscapes. Agriculture, Ecosystems & Environment 114, pp 39-56

Villa N, Paegelow M, Camacho Olmedo MT, Cornez L, Ferraty F, Ferré L, Sarda P (2007) Various approaches for predicting land cover in Mediterranean mountains. Communication in Statistics, vol 36, Simulation and Computation, Issue 1, pp 73-86

Viet J van (2006) Validation of land use change models; a case study on the Environment Explorer. WUR, Centre for Geo-information, thesis report GIRS-2006-03URL http//www.lumos.info/resources/File/validationLUchangeModels.pdf

Wainwright J, Mulligan M (2004) Environmental Modelling: Finding simplicity in complexity. Wiley

White R, Engelen G (1997) Cellular automata as the basis of integrated dynamic regional modeling. Environment and Planning B: Planning and Design 24, pp 235-246

White R, Engelen G, Uljee I (1997) The use of constrained cellular automata for high resolution modelling of urban land use dynamics. Environment and Planning B: Planning and Design 24, pp 323-343

White R, Engelen C, Uljee I, Lavalle C, Erlich D (1999) Developing an Urban Land Use Simulator for European Cities. 5th EC–GIS workshop, Italy European Communities

Widrow B, Hoff M (1960) Adaptive switching circuits. 1960 IRE WESCON Convention Record, New York, IRE, pp 96-104

Wilson AG (1974) Urban and Regional Models in Geography and Planning. New York, John Wiley

Wolfram S (1985) Some recent Results and Questions about Cellular Automata. In: Demongeot J, Solès E, Tchuente M (eds) Dynamic Systems and Cellular Automata. London, Academic Press, 399 pp

Worboys MF, Duckham M (2004) GIS: A Computing Perspective. Taylor & Francis CRC Press, 448 pp

Wu J, Marceau DJ (2002) Modelling complex ecological systems: An introduction. Ecological Modelling 153 (1-2), pp 1-6

Wu Q et al. (2006) Monitoring and predicting land use change in Beijing using remote sensing and GIS. Landscape and Urban Planning 78, pp 322-333

Yeh AG, Li X (2001) A constrained CA model for the simulation and planning of sustainable urban forms by using GIS. Environment and Planning B 28, pp 733-753

Zadeh LA (1965) Fuzzy sets. Inf. Control 8, pp 338-353

Zadeh LA (1978) Fuzzy sets as a basis for a theory of possibility. Fuzzy Sets and Systems 1, pp 3-28

Zeigler BP (1976) Theory of Modeling and Simulation. New York, Wiley, 435 pp

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ArcGIS http//www.esri.com/index.html
CLUE http//www.cluemodel.nl/
Dinamica http//www.csr.ufmg.br/dinamica/
Environment Explorer http//www.lumos.info/environmentexplorer.htm
GRASS http//grass.itc.it/index.php
Idrisi http//www.clarklabs.org/
Land Use Scanner http//www.lumos.info/landusescanner.htm
MOLAND http//moland.jrc.it/the_project.htm
LTM http//ltm.agriculture.purdue.edu/default_ltm.htm
SLEUTH http//www.ncgia.ucsb.edu/projects/gig/v2/Dnload/download.htm