Cellular Automata for modelling land use change as driven by socio-economic, environmental and policy factors

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Abstract

In this paper we present a decision support framework developed to assist planners and policy makers to analyse a wide range of policies and their associated spatial patterns. The core of this framework consists of dynamic spatial models that operate at both the micro- and macro-geographical levels. At the macro level, the modelling framework integrates several component sub-models, representing the natural, social, and economic sub-systems typifying the area studied. These are all linked to each other in a network of mutual reciprocal, influence. At the micro level, cellular automata based models determine the fate of individual parcels of land based on their individual institutional and environmental characteristics as well as on the type of activities in their neighbourhoods. Unlike conventional cellular automata, these models are defined with larger neighbourhoods, and more cell-states representing socio-economic land uses and natural land cover. Their overall dynamics are constrained by the models at the macro level. The approach permits the straightforward integration of detailed physical, environmental, and institutional variables, as well as the particulars of the transportation infrastructure. Consequently, they are suited to form the heart of spatial Decision Support Systems developed for integrated land use management or policymaking. In the DSS the models are supplemented with tools enabling the design of policy interventions as well as the analysis and evaluation of their effectiveness in attaining a desirable future for the area studied. Applications to the Island of St. Lucia (West Indies), the coastal zone of South West Sulawesi (Indonesia), the Netherlands, and Mediterranean watersheds will be presented.

1. Introduction

In the course of the last decade, researchers have made considerable progress in improving the capabilities and usefulness of Geographical Information Systems for management and policy

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purposes (Webster, 1993, 1994, Stillwell et al., 1999, Geertman and Stillwell., 2003), and GIS, in its current form, is an appropriate support tool for planning tasks that require the accurate knowledge of the detailed location of physical objects. GIS combines the great merits of spatial database management systems, graphical data manipulation, mapping, and cartographic modelling. However, ‘missing almost entirely are non-localised spatial notions such as spatial organization, configuration, pattern, spatial process, spatial dynamics, restructuring, transformation, change. Yet these are all notions that are central in urban and regional studies, and they underlie urban and regional planning especially at the strategic level’ (Couclelis, 1991 p.15). ‘Current GIS analysis is based on simple spatial geometric processing operations such as overlay comparison, proximity measures, and buffering. It does not provide optimization, iterative equation solving, and simulation capabilities necessary in planning’ (Janowski and Richard, 1994 p.339). ‘GIS have not fully realized their potential as systems to support and facilitate spatial modelling processes. They continue to handle the temporal dimension very poorly’ (Wagner, 1997 p.219). Thus, it is a major shortcoming of today’s GIS systems not to offer the possibility of dynamic and spatial modelling in the preparation and evaluation of spatial policies. And, in the case of complex systems like islands, it is to wonder how effective policies can be without the in depth understanding of the way in which activities, land-uses, and spatial interactions will change as the result of the autonomous growth potential of the system and the policy interventions imposed on it.

2. Tools for planning and decision making

We adhere to the view that a good policy decision is first of all a well-informed decision. This requires a thorough insight in the network of processes in which policy makers intervene. In order to help policy makers see through this complexity, they need to get access to integral, dynamic and spatial models representing reality as faithfully as possible. Four aspects, in particular, are prominent:

- Policy makers intervene in complete systems. Although they are to make adjustments to systems in their particular policy domain, they automatically intervene in other linked processes and may consequently cause unwanted (side) effects in the entire system. Conversely, problems that occur in the parts of the system that get their particular attention may originate from other areas of the system.
- A system inhabited by living creatures is never at equilibrium. Policy makers intervene in a dynamic reality. Their interventions cause irreversible change and even small interventions in the system may have unexpected and macroscopic consequences in the short or long term (paradigm of self-organization).
- Policy makers intervene in spatial systems. In space, processes occur in more or less defined clusters of high and low concentration. Anthropogenic and natural processes do not occur on average, neither evenly spread nor constant in time. The detailed location of activities is controlled by spatial interactions between mobile agents. The robustness and the success of a complex spatial system (such as an island or a city) particularly depend on its diversity and performance on the micro scale.
- Policy makers work in a world full of uncertainty. Despite all the scientific knowledge that is currently available, it is not possible to accurately predict the behaviour of complex natural and anthropogenic processes. It is possible, however, to make statements with a reasonable level of certainty.
Recent trends in tool and model development demonstrate that lessons have been learned from the excessive expectations in relation to models in the late 60’s and early 70’s (Lee, 1973). Now that a more realistic approach to modelling is taken and that it is understood and accepted that exact prediction in complex socio-economic or socio-environmental systems is not possible, the main purpose of models is to serve as tools to stimulate thinking and facilitate discussion, rather than to make definite statements about the future state of the system modelled. Tools also, to learn about the nature and dynamic behaviour of the real world system, and to discover how it is critically bounded. They treat socio-economic systems as integrated systems, and represent them with true care for their rich and complex behaviour. At the same time, there is a growing awareness that the spatial details, which were considered irrelevant in the past, are essential elements for the successful development of clusters of human activity and structuring of space generally. Decision supports systems, containers of models supplemented with analytical techniques and instruments, should support the explorative use of models. Thus they help in narrowing down the number of possible policy interventions, without making a predictive statement about the only or optimal intervention.

In our effort to build practical instruments for coastal zone and watershed management as well as urban and regional planning, we have developed integrated spatial simulation models and embedded them in decision support environments. To this end we created new land use simulation models, linked them to GIS, incorporated them in larger integrated models, and supplemented them with decision support tools. In this framework, advantage is taken to the extent possible of the benefits offered by GIS, such as data management, data transformation, data visualisation, cartographic modelling and spatial analysis. On the rich GIS data-layers dynamic models are built that treat geographical space as consisting of a two-dimensional matrix of small cells, typically 50 to 500 meters on the side. More in particular, the modelled region is represented by means of a constrained Cellular Automaton model, in which the cell states represent the key land uses of the area. Local land use changes are driven by and drive other kinds of physical or socio-economic processes.

3. Cellular Automata models

Cellular automata (CA) get their name from the fact that they consist of cells, like the cells on a checkerboard, and that cell states may evolve according to a simple transition rule, the automaton. A conventional cellular automaton consists of:

- a Euclidean space divided into an array of identical cells. For geographical applications a 2-dimensional array is most practical;
- a cell neighbourhood. For flow and diffusion processes the 4 or 8 immediate neighbours are sufficient, but for most socio-economic processes larger neighbourhoods are required;
- a set of discrete cell states;
- a set of transition rules, which determine the state of a cell as a function of the states of cells in the neighbourhood;
- discrete time steps, with all cell states updated simultaneously.
Cellular automata models raised, until recently, only limited interest in the geographical community, and this despite the fact that Tobler (1979) referred to them as ‘geographical models’. Originally they were developed to provide a computationally efficient technique for investigating the general nature of dynamical systems. Recent applications, however, have been directed at representing geographical systems more realistically, both in terms of the processes modelled and the geographical detail. These advances have been accompanied by an increase in the complexity of the models, and in the effort to build more realistic models Couclelis (1997). A concise overview of the application of CA models in land use modelling and spatial planning can be found in Engelen et al., (1999).

4. A generic Cellular Automata model

Over the past several years, we have developed a generic constrained cellular automata model and applied it to urban (White and Engelen, 1993, 1994; White et al. 1997) and regional (Engelen et al. 1993, 1996, 1998, 2000) cases. This model has the following characteristics:

The cell space
The cell space consists of a 2-dimensional rectangular grid of square cells each representing an area ranging from 50 to 500 m square. The grid size and shape varies according to the requirements of the application, but is typically less than 500 by 500 cells. The grid may be larger, but at the cost of long run times. The same applies to the resolution of the model: it is technically possible to increase the resolution of the CA model, but this requires to work on larger neighbourhoods as well, which increases the execution time a lot. Moreover, before increasing the resolution of the CA model, it is essential to analyse whether this would lead to any better results. Very often the basic map material will not be available or it will become unreliable at high resolution, and the processes modelled are laden with lots of uncertainty. Thus, a higher spatial resolution might give a false impression of detail and information.

The cell neighbourhood
The cell neighbourhood is defined as the circular region around the cell out to a radius of eight cells. The neighbourhood thus contains 196 cells (see Figure 1) that are arranged in 30 discrete distance zones (1, \(\sqrt{2}, 2, \sqrt{5},...\)). Depending on the resolution of the grid, the neighbourhood radius represents distances ranging from 0.4 to 4 km (for grid resolutions ranging from 50 to 500 m). This distance delimits an area that is similar to what residents and entrepreneurs commonly perceive to be their neighbourhood. It thus should be sufficient to allow local-scale spatial processes to be captured in the CA transition rules.

The cell states
The cell states represent typically the dominant land use in each cell. A distinction is made between dynamic, called Land-use Functions, and static elements, called Land-use Features. Land-use Features will not change as the result of micro-scale dynamics: they do not change location, but influence the dynamics of the Land use Functions, and thus affect the general allocation process. For example a Land use function ‘Beach tourism’ will be strongly influenced by the presence (or absence) of the land use feature ‘Beach’. Our models will operate on a maximum of 32 states, 16 of which are land use...
functions and 16 are land use features. Clearly, raising the number of states in the CA will increase, in theory at least, the number of possible state transitions of each cell, and defining the transition rules of the model will become more cumbersome. Again, it requires special attention on behalf of the model developer to keep this complexity within limits. It is only useful to distinguish between land uses if and only if these land uses behave differently in space. If however their spatial dynamic is very similar then land uses can just as well be combined into a single land use function.

The neighbourhood effect
The fundamental idea of a CA is that the state of a cell at any time depends on the states of the cells within its neighbourhood. Thus a neighbourhood effect must be calculated for each of the land use function states to which the cell could be converted. In our models, the neighbourhood effect represents the attraction (positive) and repulsion (negative) effects of the various land uses and land covers within the neighbourhood (see Figure 1). In general, cells that are more distant in the neighbourhood will have a smaller effect. Thus each cell in a neighbourhood will receive a weight according to its state and its distance from the central cell. Specifically, the neighbourhood effect is calculated as:

\[ N_j = \sum_x \sum_d w_{kxd} I_{xd} \]  

Where: \( w_{kxd} \) = the weighting parameter applied to land use \( k \) at position \( x \) in distance zone \( d \) of the neighbourhood, and \( I_{xd} \) = the Dirac delta function: \( I_{xd} = 1 \) if the cell is occupied by land use \( k \); otherwise, \( I_{xd} = 0 \)

Figure 1: For the calculation of the neighbourhood effect, a circular neighbourhood consisting of 196 cells is applied (left). For each land use function, the transition rule is a weighted sum of distance functions calculated relative to all other land use functions and features (Right).

The transition rules
For cellular automata developed on a homogeneous cell space, a vector of transition potentials (one potential for each function) is calculated for each cell from the neighbourhood effect. The deterministic value is given a stochastic perturbation (using a modified extreme value distribution), such that most values are changed very little but a few are changed significantly:
\[ P_j = vN_j \] (3)

Where: \( P_j \) = the potential of the cell for land use \( j \)
\( v \) = a scalable random perturbation term
\( N_j \) = the neighbourhood effect on the cell for land use \( j \)

For cellular automata developed on a non-homogeneous cell space, the transition potential will include next to the neighbourhood effect also the attributes representing the details of the cell space. In the next section, we will discuss different ways in which this can be done.

Once the transition potentials for all cells and all functions have been calculated, the transition rule is to change each cell to the state for which it has the highest potential - subject, however to the constraint that the number of cells in each state must be equal to the number demanded at that iteration. Thus all cells are ranked by their highest potential, and cell transitions begin with the highest ranked cell and proceed downward. The number of cells required is determined external to the cellular model in a ‘macro-model’ as will be explained in section 5. It is imposed as a constraint on the cellular automaton. When a sufficient number of cells of a particular land use have been achieved, the potentials for that land use are subsequently ignored in determining cell transitions; the result is that some cells are not in the state for which they have the highest potential. Each cell is subject to this transition algorithm at each iteration, although most of the resulting “transitions” are from a state to itself, that is, the cell remains in its current state.

5. Cellular Automata as the core of integrated models

An initial spatial configuration on a grid of homogeneous cells, a neighbourhood and transition rules are in principle sufficient to cause a traditional cellular automaton to evolve over time, in some cases even indefinitely (Langton, 1992). Most of the theoretical work done in the field consists precisely in the analysis of the patterns thus generated (Wolfram, 1994; Couclelis, 1988). Real world socio-economic systems, however, develop in geographical space that have heterogeneities at all levels of detail and are shaped by interaction processes that take place at different geographical scales. Cellular automata models that are aimed at representing geographical systems genuinely should accommodate for these aspects of reality. In this section we will discuss ways in which cellular automata models can incorporate ‘macroscopic’ interaction processes which are beyond the reach of the cellular space of the modelled system as well as ‘microscopic’ attributes that represent the non-homogeneous, dynamic nature of the geographical space within which the dynamics unfold.

Socio-economic systems are shaped by interaction processes that take place at various geographical scales, some of which are very local and within the reach of the neighbourhood, some of which are beyond the reach of the cellular space of the modelled system. In order to incorporate the dynamics caused by long range processes, phenomena beyond the reach of the neighbourhood are dealt with through the introduction of larger geographical entities (see for example: Roy and Snickars (1993) and Batty and Xie (1994)) or through the linkage of cellular automata models with more traditional dynamic models (see for example: Engelen et al., 1993, 1995). In most of our work, we have chosen to implement the latter: in the simulation context, the dynamic model calculates the overall growth of the system as a result of its internal
‘macro’-dynamics and its exchanges with the world external to the model. The macro-model ‘forces’ its growth, as a constraint, upon the cellular model. The latter allocates the growth to specific cells based on its ‘micro’ CA-dynamics. The results of the allocation process are returned to the macro model and may affect the macro-dynamics. We have coupled different types of ‘macro’ models to cellular automata ‘micro’ models (see Figure 2):

1. In the simplest of cases, the macro-model consists of a set of trend lines, one trend line for each land use modelled. We have applied this solution to a research model simulating the growth of the city of Cincinnati in the USA (White et al., 1997). The trend line is obtained from the analysis of data sources, other models, or scenarios defined by the user;

2. A more satisfactory solution consists in using a sort of dynamic systems model to drive the dynamics of the cellular automaton (Engelen et al., 1993). This model represents the integrated dynamics of the demographic, social, economic and institutional processes characterising the modelled region at the global level (for example: the whole city, the whole island, or the whole coastal zone). The resulting growth drives the cellular model, which on the basis of its own local dynamics, takes care of the precise location and re-organisation of human land use and natural land cover. We have applied this type of model successfully to the island of St. Lucia in the Caribbean (White et al., 1997, 2000), and to a large coastal zone near Ujung Pandang in SW Sulawesi (Indonesia) (Uljee, et al., 1996; Kok et al., 1997). These examples are dealt with in the section 6.1 respectively section 7 of this paper.

3. Finally, a most powerful representation is obtained if a regionalised dynamic macro-model is applied. This solution is most useful if there is evidence that the structuring of space has a distinct macro-geographical component to it. This is typically the case if the area modelled is large. We have coupled a dynamic spatial interaction based model to a cellular automata model in an application for the Netherlands (Engelen et al., 1998b) and will discuss it in section 6.2.

Whereas purely theoretical problems (See for example White and Engelen, 1993), can be studied in a homogeneous space, more realistic spatial problems are set in spaces that have idiosyncrasies and heterogeneities at all levels of detail. This requires for the homogeneous cell space of the cellular automata to be replaced by a space in which each cell has an inherent set of attributes representing relevant physical, environmental, social, economic, historical or institutional characteristics. This modification is attained by linking CA models with GIS (Engelen et al., 1993; Batty and Xie, 1994; Clarke et al., 1997), or by linking it to other kinds of cellular models (Engelen et al., 2000). In the first case, a linkage to GIS, the attributes are mostly static descriptions of the cellular space. In the latter case, a linkage to other cellular models, the attributes may contain descriptions of space that change dynamically in the course of a simulation. We have developed applications of both kinds (see Figure 2):
The cellular space of cellular automata is structurally not different from the cellular representation of space in raster GIS: they both are basically a grid cell partition of a geographical area. This similarity enables an easy linkage between a GIS and the cellular automata model from a conceptual and technical point of view. It suffices to ascertain that the grid reference systems of the CA model and that of the GIS coincide and that a one to one relationship between the cells of both is established.

1. In the simplest of cases, a vector of suitabilities, one suitability for each land use function, can describe each cell. These suitabilities are defined as a weighted sum or product of a series of physical, environmental, infrastructural, historical and institutional factors. For computational purposes, they are normalised to values in the range (0 – 1), and represent the inherent capacity of a cell to support a particular activity or land use. They are generated in a GIS and imported into the cellular simulation environment. They remain constant during the simulation unless the user interrupts the run and edits them manually. Special purpose editors are available in the simulation environment for that purpose.

2. However, for spatial planning and policy making purposes, there are good practical reasons to distinguish in the model between the attributes describing the ‘physical suitabilities’, ‘zoning regulations’, and ‘accessibilities’ of the cellular space:
   a) First, each cell is characterised by a vector of physical suitabilities, one suitability for each land use taking part in the dynamics. They are composite measures calculated on the basis of physical, and environmental characterising each cell. They are further calculated as explained in case 1 above;
b) Second, each cell has associated with it its zoning status for various land uses, and for various periods and is calculated from different factors characterising the institutional and legal status of the area and parts thereof;

c) Finally, each cell is associated with a vector of accessibility factors, again one for each land use. These factors represent the importance of access to the transportation networks for the various land uses or activities: some activities, like ‘commerce’, require better accessibility than others, such as ‘agriculture’. However, most natural land cover categories, are best located in areas with poor accessible because they run the risk to be fragmented by the transportation networks. The transportation networks are represented by cell-centred vectors and appear superimposed on the cell grid. Accessibilities are calculated as a function of distance from the cell to the nearest point on the network. Like the physical suitabilities, they are expressed in values in the range 0-1. A different expression is used for land-uses favouring good accessibility:

\[ A_j = \frac{a_j}{D + a_j} \]  \hspace{1cm} (4)

or poor accessibility:

\[ A_j = \frac{D}{D + a_j} \]  \hspace{1cm} (5)

Where:
- \( A_j \) = the accessibility of the cell for land use \( j \)
- \( D \) = the Euclidean distance from the cell to the nearest cell through which the network passes;
- \( a_j \) = a coefficient representing the importance of accessibility to the network for land use \( j \). In more sophisticated applications, this coefficient is a function of the kind of network or the type of link within the network.

The combined effect of suitabilities, accessibilities, and zoning is that every cell is essentially unique in its qualities with respect to possible land uses. And it is on this highly differentiated cell space that the dynamics of the cellular automata itself unfold. If the cellular automata model is running in a cellular space defined as explained, the expression (3) for the transition rule becomes:

\[ P_j = v A_j S_j Z_j N_j \]  \hspace{1cm} (6)

Where:
- \( P_j \) = the potential of the cell for land use \( j \)
- \( v \) = a scalable random perturbation term,
- \( A_j \) = accessibility of the cell to the road network,
- \( S_j \) = the intrinsic suitability of the cell for land use \( j \)
- \( Z_j \) = the zoning status of the cell for land use \( j \)
- \( N_j \) = the neighbourhood effect on the cell for land use \( j \)

3. Linkages with GIS applications have the great advantage of simplicity. They can take full advantage of the tools available in GIS to generate the suitability and zoning maps. But, they suffer of the fact that the GIS information is most often static in nature. For some
applications this is hardly a problem. For example, the physical and environmental suitability of plots for ‘industry’ in a city will not change dramatically in the course of a simulation. But, for other land uses, such as ‘agriculture’ for instance, the physical suitability may change rapidly and fundamentally. For instance, in a Mediterranean coastal plain, the amount and quality of irrigation water available from the aquifer is a determining factor in the physical suitability for agriculture in general and for citrus crops in particular. In turn, the replenishment of the aquifer is highly subject to the variability in the climate and weather conditions. In such cases, it may be highly preferential to couple the cellular automata dynamics to a cellular model of another kind representing the physical and environmental dynamics of the area. Like for linkages with GIS it is important that the grids, on which both models are developed, coincide, and that there is a one to one relationship between the cells of both models. In section 6.3 we will describe a case in which a cellular automata land use model has been coupled to a spatialised soil / vegetation / atmosphere transfer model (Mulligan, 1998).

4. In our most recent applications (Engelen et al., 2000, Engelen 2003), in principle any factor available from a GIS or a variable from another kind of cellular model can be incorporated into the cellular automata model as an attribute of the cellular space. To that effect, the simulation environment has been equipped with a parser capable of interpreting the transition rule defined by the model developer at run time. This feature is extremely powerful. It not only allows for the integration of cell attributes available from linked GIS layers but also cell variables, available from linked cellular models.

Both the coupling to macro models and to other kinds of cellular models, demonstrate how cellular automata can act as the integrating elements in models representing human and environmental processes that operate at disparate spatial and temporal scales. In order to attain this level of integration, the computational framework within which the model is implemented should be sufficiently open ended and flexible. In the next sections we will discuss how we have dealt with this problem in a number of examples.

6. Three examples

In this section, we present three examples of integrated models in which cellular automata play an important role in coupling the constituting model components. We present these specific examples to show the generic applicability of the modelling approach outlined above and to demonstrate the theoretical points made. Each of the models presented have been developed with a practical use in mind. The order in which the examples are presented is one of growing level of integration and complexity.

6.1. St. Lucia

The St. Lucia model (in fact the model is called SimLucia) is presented because it exemplifies the application of the generic model outlined above to a case of limited

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II The application to the island of St. Lucia is described at much greater detail in: Engelen et al., 1998a; White et al., 1997, 2000. The SimLucia model can be downloaded from the RIKS web page: http://www.rik.nl/RiksGeo/proj_sim.htm
geographical size. The island is less than 45 by 30 km in size and most of its macro-economic and demographic interactions with the world outside the island apply for the entire territory. Thus, the dynamics of the island can be sufficiently represented by means of a model representing it as a single entity interacting with the external world. The model was originally developed for UNEP\textsuperscript{III} to analyse the effects of climate change, in particular temperature change and sea level rise, on the socio-economics of the island and on its land use.

Climate change in the Wider Caribbean Region is expected to have an important impact on the physical, environmental, social and economic systems (Maul, 1993). Socio-economic systems in the region are already stressed considerably due to demographic, economic and environmental factors, and climate change will exacerbate this situation. Hence, formal instruments to study the effects of climate change on socio-economic systems require realistic representations of their actual state and of the processes that will cause them to change in the future. Their temporal and spatial dynamics should be well represented, because climate change is affecting socio-economic systems through mechanisms at very different geographical scales: at the macro-scale causing changes in the exchanges with the world system through changed demands, exports, imports and migrations; and at the micro-scale causing the retreat, relocation and possible disappearance of activities.

We developed an explicitly dynamic and spatial modelling framework operating at two geographical levels: the \textit{macro-level} describes the macro-economic and long-range spatial interactions, and the \textit{micro-level} describes the short-range interactions and location choices. At the macro-level, the St. Lucia is modelled as a single region --as one centroid interacting with the external world. Hence, a single set of linked dynamic equations generates the evolution in time of the integrated socio-economic and environmental systems. The growth coefficients thus calculated are fed into a cellular model, operating on the micro-level, which allocates the socio-economic growth to island cells of 250 by 250 meter. This allocation mechanism is based on micro-level spatial interactions specified in cellular automata rules and based on physical suitability measures retrieved from a GIS. The cellular model will return the results of the allocation to the macro-level, to inform it about the amount of open space left and its suitability for specific land uses. Thus the full coupling of the macro and micro scales is guaranteed.

At the macro-level essentially three coupled sub-systems are modelled: the natural, social, and economic sub-systems. The \textit{economic sub-system} is modelled by means of a highly aggregated input-output model, coupled with the demographic model (through a wealth indicator and household demands), with the natural system (climate changes influence external demand) and with the Micro-level via a land density expression (activities require space). The economy is aggregated into four sectors: agriculture, industry and quarries, trade and services, and tourism. In the \textit{social sub-system} the demography is modelled as a single population group growing as the result of births, deaths, and migration. The birth rate is specified to follow a long term trend, while mortality and migration rates depend on both forecasted long term structural trends, and on the well-being of the population as indicated by the employment participation rate.

\textsuperscript{III} United Nation Environment Programme, UNEP/CAR/RCU, Kingston, Jamaica
The total population is subdivided into an urban and a rural class according to a scenario based on census data as well as on a hypothesis from the user. The natural sub-system consists of a set of linked relations representing the expected change in time of sea level and temperature, and their effects on the loss of land, precipitation, storm frequency, and external demands for services and products produced.

The model calculates the changes in employment per sector and the growth of the population. New jobs and new people require space to support their residential and economic activities. In the model the translation of economic and residential activity into space is performed by means of the land density expression. The land density is a function of the total amount of land available, the suitability of that land for the activities carried out, and the land (and its suitability) already occupied. Generally speaking, land density will increase if land is getting scarce. But it will decrease if the land occupied is getting marginal for use by the specific activity. The total amount of land required by each activity is used as an input to the micro-level part of the model.

At the micro-level, St. Lucia is represented by means of a grid of 186 rows (N-S) by 121 columns (E-W) or 22506 cells. A cell size of 250 m has been chosen. This size represents well the actual plot sizes for tourism, industrial, service and residential land use. But, it is hardly detailed enough to represent the relief of St. Lucia, which is typified by very strong changes in the elevation over very short horizontal distances. Each cell is in one of 15 possible states, each representing a land-use. Land use functions are: natural vegetation (mainly bush), forest (mainly secondary forest), agriculture, industry and quarries, trade and services, tourism, rural residential, urban residential. Land-use features are: forest reserve; mangroves; sea; beach; coral reef; terminals, ports, and airports; infrastructure, water, and electricity.

The geographical (physical, environmental, institutional, infrastructural, ...) characteristics of the island are represented in the relief map, the suitability maps, and the (road network) accessibility maps. The cellular automata neighbourhood consists of 196 cells and a hierarchical transition rule is applied: first it is calculated whether a cell is above or below sea level and available for land-based activities (as a result of sea level rise). Next the neighbourhood effect is calculated, and finally, the transition rule will change cells to the state for which their transition potential is highest, unless no more cells in this state are required by the macro model.

With the model different scenarios have been run and compared to one another. Typically a simulation runs from 1990 till 2030. In this 40-year period, temperature is expected to rise by some 2ºC and sea level may rise by as much as 20 cm (see for example: Maul, 1993). From the simulations we conclude that climate change could have negative consequences for the tourism sector, mostly because much of the tourism in St. Lucia is beach dependent, and beaches may be affected strongly by sea level rise on this island that has only few and narrow beaches in an otherwise mountainous country. Some beaches may even disappear entirely unless they are protected or replenished artificially. From the simulations we can also conclude that demographic pressure may become more of a problem in St. Lucia than climate change. Due to population growth (from 134110 inhabitants in 1990, till +/- 190500 in 2030) a strong urbanisation takes place north of the capital Castries. But there is also an overflow to the southern tip of the island. New residents are attracted to the south by the rapid industrial development near the town of Vieux Fort and the Hewanorra airport (see Figure 3).
6.2. Environment Explorer

The Environment Explorer model is conceptually not very different from the SimLucia model in that it consists of a layered model with a cellular automata micro-model which dynamics are constrained by a socio-economic macro-model. However, the model is applied to the full territory of the Netherlands covering some 40,000 km² and 18 million people (Engelen et al., 2003). Its geographical extent as well as the geographic distribution of centres of high and low concentration of population do not allow to represent the modelled region as a single centroid in interaction with the surrounding world. On the contrary, in order to get a good understanding of the dynamic processes that change the spatial configuration of the country, it is important to distinguish between processes that operate at different geographical scales. To that effect, the Environment Explorer features a model that operates at three geographic levels: the National, the Regional and the Local cellular level (see Figure 4).

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Figure 3: SimLucia: land use, jobs and population in 2010 and 2030 resulting from a typical simulation run.

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The Environment Explorer has been developed with and for the National Institute of Public Health and the Environment, P.O. Box 1, 3720 BA Bilthoven, The Netherlands. The technical aspects of the Environment Explorer are explained (in Dutch) in more detail in: Engelen et al., 1998b. Additional information can also be obtained from: http://www.riks.nl/RiksGeo/proj_lov.htm
At the National level, the model integrates national figures taken from economic and demographic growth scenarios in which the developments of the Netherlands are studied in a European and world context. The economic activities are grouped into 8 main categories: crop farming, dairy farming, greenhouse farming, other farming, industry, services, socio-cultural, and recreation. The demographic scenarios are translated into two residential categories: high and low-density residential housing. This grouping of economic and demographic functions reflects their specific spatial requirements as well as the quality and availability of data at the three geographical levels of the model.

Next, at the Regional level consisting of 40 large administrative regions (called COROP regions), a dynamic spatial interaction based model arranges for the spatial allocation of national growth as well as for the inter-regional migration of activities and residents driven by long-range interaction processes. The latter take into account the intrinsic economic and demographic growth potentials of the regions, their geographical location relative to one another, and their relative position compared to the neighbouring countries as well as their access points to distant markets via the air- and seaports. One of two principles is applied: for activities such as housing, a relative potential calculation is applied, for other activities, such as services, for which economic considerations are more important, a relative profit criterion is applied.

At the regional level 4 sub-models can be distinguished:
1. a regional economic module calculates the amount of production and employment for each economic activity;
2. a regional demographic module deals with the demand for housing;
3. an allocation module translates the regional growth into spatial claims at the local (cellular) level. Two principles are applied at this level:
   a. allocation of land is policy driven and is imposed directly on the local level. This principle applies for land uses such as natural land and some of the agricultural activities. It reflects the fact that for these activities policy documents specify the amount of land that is to be allocated or reserved in each region;
   b. or, the principle of supply and demand is applied to regulate the densification of land use as well as spatial allocation. This principle applies in particular to housing and most of the economic activities.

4. a transportation module controls the exchanges of goods and people between the different regions. The flows of goods and people are very much the result of regional difference in relative attractiveness of the individual regions. The position of the regions relative to one another and their interconnection via the national transportation systems play an important role in this.

Finally, at the **Local level** the Netherlands is represented as a grid consisting of some 350000 cells of 500 by 500 m each. A cellular automata based model handles the dynamic allocation of the regional spatial claims. The states of the cellular automata model are the dominant land uses in each cell of the grid. A cell is in one of 22 possible land use states, 10 of which are land use functions. The transition from one state to the other is determined by the combination of the 4 locational characteristics discussed in section 4:
   • the **neighbourhood effect** calculated in a circular neighbourhood consisting of the 196 nearest neighbours;
   • the **suitability maps**, one for each land use function modelled. These maps are prepared in a GIS based on some 15 factor maps determining the physical appropriateness of the cells to support each type of land use;
   • the **zoning maps**, one for each land use function modelled, also prepared in a GIS. For three planning periods, to be determined by the user (example: 1990-2005, 2005-2015, and 2015-2030), they specify which cells can be taken in by each land-use;
   • the **accessibility map**. The accessibility for each land use function is calculated in the model relative to a road network (the LMS-road network used by the Ministry of Transport, Public Works and Water Management) consisting of the motorways and main national and regional roads.

The linkage between the models at the regional and cellular level is bi-directional and very intense. Very much along the lines of what was explained for SimLucia, the regional model will impose on the cellular model the growth coefficients for the different land use functions modelled, and, the cellular model will return to the regional model constraints on the availability and the quality of the space available for further expansion of each type of economic or housing activity and the associated land use functions. This information is an input in the interaction mechanism at the regional level and it will influence strongly the relative attractiveness of the individual regions. Hence, as regions in the course of time are gradually running out of space for one or the other activity, they will lose part of their competitive edge and will exert less attraction. Growth is consequently diverted to other, more attractive regions. This kind of linkage of models is very novel in the field and is very beneficial to both kinds of models: on the one hand, the dynamic spatial interaction based model is dynamically
updated with detailed information about the morphological and environmental characteristics of its regions, and on the other hand, the cellular automata model can take into account the effects of spatial processes which are beyond the reach of the cellular neighbourhood.

Another novel feature in the Environment Explorer model, which is directly linked to the previous point, is the fact that its CA-model is not a single CA-model, rather it is a set of 40 CA-models running simultaneously, one for each COROP region. Hence the regional structure of the model is not only reflected at the regional level proper, but also at the cellular level. At each time step in a simulation, the output from the regional model for each region is applied to the cells belonging to that region at the cellular level. Yet, at the cellular level the regions are not isolated from one another. Rather, they fit together like the pieces of a jigsaw to cover the full territory and spatial contiguity between the different cellular models is guaranteed as the cellular neighbourhoods will extend into neighbouring COROP regions. As a result, cells near the border of one region, will include in their neighbourhood effects (see section 4) information that is obtained from the neighbouring region. The beauty of this principle resides in the fact that geographical structures can be modelled across borders in all their morphological complexity (Engelen et al., 1997). This tends to be a problem with other kinds of dynamic spatial models.

6.3. The MODULUS model

The MODULUS model is presented here, because it exemplifies how cellular automata models can be very valuable instruments in linking socio-economic and physical models into a fully integrated model running at multiple temporal and spatial scales. The MODULUS model has been developed as part of a European Commission research project (EU-DG12 ENV4-CT97-0685), aimed at the development of a powerful instrument for integrated policy making in the domains of land degradation and desertification in the coastal watersheds of the Northern Mediterranean. To that end, MODULUS selected existing models from complementary EU projects. It adapted them with a view of their integration into an instrument for practical policy making. To enable the technical integration of the adapted models, a state of the art software framework was developed based on component technology and on COM and ActiveX in particular. The great merit of the latter framework is its level of generic applicability to other cases and the ease with which new component models can be integrated into the system.

The MODULUS model is an explicitly spatial and dynamic simulation model. Each of its component sub-models runs at the appropriate time scales and spatial scales. Thus, some of the processes modelled have time steps expressed in minutes, while others run once a year. As for the spatial resolution, most of the models run on a 1 ha grid, but other run on a 25 ha grid or on irregular geographical areas. A typical simulation run covers a 30-year period.

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The work so far carried out in the MODULUS project and the resulting MODULUS model is described in much greater detail in the interim report of the project (Engelen et al, 1999). More information on MODULUS can also be obtained from: http://www.riks.nl/RiksGeo/proj_mod.htm
The model can be run under a very wide range of hypothesis and scenarios and can visualise the short and long term effects of these. From a management point of view this model is a very valuable instrument to the decision maker in that it represents the physical and the anthropogenic causes of land degradation in a very elaborate and explicit manner.

From the integration scheme in Figure 5, it may be clear how different sub-models interact with one another. These sub-models are grouped in 4 main categories: weather, vegetation, water, and human.

The role of the individual models in the connection scheme can be summarised as follows:

- The Climate and weather model runs daily. It calculates for each day the time of sunrise and sunset and the average solar radiation map at the top of the atmosphere between sunrise and sunset. The average solar radiation is then corrected for cloud cover as well as for the slope and aspect of each cell. The average temperature per cell is updated monthly. Further the model generates for the day a detailed time series (expressed in minutes and bucket-tip times) for precipitation for the study areas based on data from at least 1 AWS weather station.

- The Hillslope hydrology model runs daily, but integrates internally over bucket-tip times. This model deals with the soil hydraulic properties and calculates the water budget. It calculates the interception, infiltration, soil moisture, transpiration, soil evaporation, overland flow, surface recharge, and erosion.

- The Surface water model runs daily. It represents the river, canal, and water reservoir system, and the water quality of the surface water. It calculates the river flows per stream order, the sinkhole flows, the catchment recharge flows, and the PO$_4$ and NO$_3$ concentrations. The model runs on irregular shaped, natural defined areas—the catchments and sub-catchments.
• The Ground water model represents the depletion, recharge and pollution of the aquifer. It calculates the aquifer water height, salt concentration and the fluxes between cells. The aquifer model runs monthly and on a cell resolution of 500 by 500 m.

• The Natural vegetation model runs monthly. It represents the processes of growth, succession and decline of the natural vegetation at the community level. It calculates the leaf area index, the vegetation cover fraction, and the rooting depth. The natural vegetation model is a rule-based model, applied on each individual cell of the case regions. It is supplemented with a cellular seed diffusion model, which produces a seed biomass linking the individual cells.

• The Plant growth model runs daily. It represents the processes of growth of plants, both commercial crops and natural vegetation, and calculates the leaf biomass, root biomass, leaf area index and the vegetation cover fraction.

• The Land use model runs yearly. It is a cellular automata based model which allocates on a 1 ha grid the land claims resulting from demographic changes, as well as the dynamics in the agricultural and non-agricultural part of the economy. The allocation methodology takes into consideration the activity specific attractivity of cells in terms of their suitability, zoning regulations and accessibility to the road transportation infrastructure. The overall demographic and economic growth is not calculated in the model; rather it is entered in the form of scenarios.

• The Irrigation model runs twice daily. It is a rule-based model representing the farmer’s decision to switch on the water pumps and start the irrigation. It is applied to each 1ha cell and calculates the pump status, volume to be pumped, water extraction from canals, volume of frost sprinkling water, irrigation water volume, irrigation and frost water salt concentrations, and the total yearly short-term exploitation costs.

• The Crop type decision model runs on a yearly basis. It is a rule-based model representing the crop-choices made by farmers as a function of changing physical, socio-economic and institutional conditions and circumstances. It is applied to each 1ha cell and calculates the crop type, crop water requirements, water source, presence of boreholes, borehole depth, pumping capacity, air mixer deployment and the total yearly long term exploitation costs.

The MODULUS model relies heavily on GIS data. As an input it requires some 25 GIS layers (raster maps, mostly at 100 meter resolution), and its 9 sub-models update, each at their dedicated simulation time step, some 50 output maps. All the output maps are simultaneously available to the user. Hence, during the simulation the user can watch the evolution of the modelled region by means of any combination of the 50 mapped variables. Some of the output maps represent a final output variable of the integral model, but most maps are generated or updated by one model to serve as an input for the next model.

It is beyond the context of this paper to dwell on the individual sub-models. Suffices to say that very different modelling techniques are used in the sub-models, ranging from sets of partial differential equations to purely rule based models. In this paper, however, we would like to stress the core position of the cellular automata Land use model in integrating the different socio-economic and physical aspects of the model. The land use model consists of a micro model with the general characteristics explained in section 4: the cellular dynamics develop on a 1 ha grid, and the neighbourhood consists of a maximum of 196 cells. The cell states are limited to 5: natural land, agricultural
land, high-density residential land, low-density residential land, and industrial land (see Figure 6). The growth and decline of each land use category is fully driven by a set of trend lines. They are fed into the Cellular micro model. The CA land use model will allocate the new growth to the different cells in the modelled region. Thus, the model will deal with the expansion of the main land use categories: industry, residential and agricultural. As a result natural land will be lost to the expanding human activities and associated land uses, and land abandoned by human activities will be available to re-colonisation by natural vegetation. In the allocation process, the CA model takes as an input for each cell and each land use function information on zoning regulations and the accessibility to the road network. As for the suitabilities, this information is available to the CA model partly as static maps, but partly also as dynamic map layers, which are updated by the MODULUS sub-models and used in the CA-algorithm. For instance, information on the relief, and aspect of cells is available as static GIS information, while weather conditions, changing climate, changing soil properties and hydrologic conditions, availability of ground and surface water, and the status of wells are all available as dynamic map layers in the allocation process. These are all essential factors in the analysis of the level of sustenance of agriculture in the region.

![Figure 6: Land uses modelled in the MODULUS Land Use sub-model. Applied to the Marina Baixa region in Spain.](image)

Combined with the Land use sub-module, the more precise utilisation of agricultural land is defined by the Crop type Decision model (Oxley et al., 1999). Based on a rule base and a reasoning mechanism mimicking the behaviour of farmers to the extent possible, this model selects one crop type, from a total of six main crop types, to be grown in each ‘agricultural’ cell (see Figure 7). The decisions made by the farmers are influenced among others by: the subsidies paid for growing the crop, the overall demand for the crop, the production costs, the costs of changing to other crops, the physical and institutional suitability of the cell where the crop is grown, including in particular water availability.

In a similar manner, the Natural vegetation sub-model (ModMED et al., 1999) will specify in a more detailed manner the type of natural vegetation that is developing in a particular ‘natural’ cell. Again, a rule-based model is applied for that purpose. It calculates the state transitions between some 15 vegetation types that are typical for the Mediterranean regions modelled. It shows how the natural land cover evolves from grassland vegetation into the climax vegetation based on the physical properties of the
land, the climatic conditions, seed dispersal, naturally occurring fires and anthropogenic influences such as extensive grazing (see Figure 8).

Figure 7: Crops modelled in the MODULUS Crop type Decision sub-model. Applied to the Marina Baixa region in Spain.

Figure 8: Natural vegetation types modelled in the MODULUS Natural Vegetation sub-model. Applied to the Marina Baixa region in Spain.

The coupled Land use, Crop type decision and Natural vegetation models present a very powerful and detailed picture of the changing land use / land cover in the modelled region in no less than some 25 land use / land cover categories. The total rule base driving the land use dynamics is rather large. Better than what is the case in traditional cellular automata models, this rule base takes into consideration all kinds of information and processes at the level of the individual cells or the region as a whole. The application shows the core position of the Cellular automata in this integration scheme.

7. From the model to the Decision maker

Few analysts or policy makers will contradict the statement that nearly all problems in the field of spatial planning and integrated land use management are complicated, complex and ill-defined in nature. Models, mathematical models in particular, are instruments to solve structured and strictly defined problems: given a strict formal solution method or algorithm, and given that all the inputs required by this algorithm are provided; the model will produce a fully specified output. Thus, there seems to exist an
incompatibility between the needs and the tools: ill-defined problems, but tools for solving strictly defined problems. The question at hand then is: are models useful instruments for decision makers and how can they be made more useful to them? This is where Decision Support Systems become useful instruments.

Decision Support Systems (DSS) are computer-based information systems developed to assist decision makers address semi-structured (or ill-defined) tasks in a specific decision domain. They provide support of a formal type by allowing decision makers to ‘access’ and use ‘data’ and appropriate ‘analytic models’ (Najdawi and Stylianou, 1993). The terms ‘semi-structured’ and ‘appropriate’ in this definition refer to the fact that Decision Support Systems are typically applied to find answers for problems that, due to their specific nature and complexity lack an unambiguous solution method. Rather, the unique answer is approximated by making use of the most appropriate analytical solution methods available. Thus, the DSS provides the decision maker with a suit of ‘analytic tools’, which are considered appropriate for the decision domain. Typically decision models, statistical and operations research methods, as well as tools to portray, compare and evaluate different decision alternatives, are available from the model base of the DSS. Even more essential in the model base are the domain specific models capable of grasping the complexities of the system and the problems studied.

Integrated models play a key role in the model base of a DSS in the sense that their constituting sub-models are covering, at the least in part, the (sub-)domains related to the decision problem, but more so because a good integrated model features the essential linkages between the sub-models and the related (sub-)domains. Thus, the user of the DSS gets immediate access to very rich and operational knowledge of the decision domain. However, integrated models of the kind presented in section 6 are not sufficient. Rather the DSS should stimulate and facilitate the explorative learning behaviour of the decision maker, because better informed policy makers are better equipped to make better policies that bring the systems they are to manage on a better path towards sustainability. Thus, the prime role of the models and the Decision Support Systems is awareness raising, understanding and education, rather than the decision-making act itself. The models therefore should give an adequate and truthful representation of the real world system, and they should be supplemented with tools that enable the decision maker to prepare the input of his analysis, generate decision alternatives, perform the analysis, and compare and evaluate the outcomes of the different alternatives generated. A well-designed user-friendly interface should enable to structure the policy exercises carried out with the model. The same interface should increase the transparency of the model and the DSS as much as possible: at any point in time, the user should have access to the background information required to understand the processes and models he is working with and the numbers they generate. Without this information, models become black boxes and no learning takes place.

Another important role for the user-interface is in presenting the information that the DSS contains and in structuring the inputs that it requires in a manner relating to the life world of the decision maker rather than that of the developers of models and analytical tools. It enables the user to make decisions on the basis of a consistent line of reasoning and suggests solutions in ways that make intuitive sense to him (Holtzman, 1989).
MODULUS allows the policy maker to work with the models in a structured manner. Thus, he can get a better understanding of the system he is to manage.

In the Decision Support System for Integrated Coastal Zone Management (called RamCo\textsuperscript{VI}) developed for the Dutch Coastal Zone Management Centre\textsuperscript{VII}, the interface is designed in accordance with the scheme shown in Figure 9. The coastal system (box: System) is represented by means of an integral systems dynamics model. Because of its autonomous dynamics, this coastal system evolves into new states as time goes by (box: Resulting state). The policy relevant aspects of new states is captured and synthesised in a number of indicators. The policy maker should begin any policy exercise, aimed at selecting ways of altering the autonomous dynamics or future state of the coastal system, with a clearly defined set of criteria defining the desired state at a particular point in time (box: Preferred state). In order to bring the actual state of the coastal system closer to the preferred state, the policy maker can intervene in the system by means of policy measures (box: Policy measures). In an iterative process, he can tune his policy measures in an attempt to approach the preferred state with a minimum amount of effort and costs. The robustness of the chosen policy measures can be tested by imposing effects on the system that in the real world are beyond his control. These effects are called scenarios (box: Scenarios).

The user-interface of RamCo features for each of the boxes in the above scheme a specific window and view on the underlying model. Each view shows in a graphical manner how policy relevant features relate to the processes modelled.

1. The System diagram View shows an overview of the structure of the system modelled at the most synthetic level by means of boxes connected by arrows. At the very heart of the RamCo DSS is a system dynamics model representing the physical, environmental, economic and social processes typifying the dynamics of a coastal zone generally and the coastal zone of SW Sulawesi (Indonesia) in particular. When one of the boxes is

\textsuperscript{VI}The work carried out in relation to ‘RamCo: Integral Assessment Module for Coastal Zone Management’ is explained at length in Uljee \textit{et al}., 1996 and in Kok \textit{et al}., 1997. More information on RamCO can also be obtained from: http://www.riks.nl/RiksGeo/proj_ram.htm

\textsuperscript{VII}The Coastal Zone Management Centre, National Institute for Coastal and Marine Management/RIKZ, P.O. Box 20907, 2500 EX The Hague, The Netherlands
2. The *Scenarios View* shows the parts of the model that are most subject to external influences and where hypothesis about these influences can be entered. To name in this context are: precipitation variability, prices on the international markets for the goods and services produced in the coastal zone, population growth, migration and rural exodus, income development and fishing effort;

3. The *Policy options View* shows the parts of the model that are subject to policy interventions. The major policy options retained in RamCo are: reforestation, marine resources and mangrove rehabilitation, dam construction and storage lake maintenance, waste water treatment, investment in industry and infrastructure, and fisheries regulations;

4. The *Impacts View* shows the parts of the model containing the summarised information and policy indicators required to evaluate the success of scenario and policy options tried out on the system. In general the indicators express the level of sustainability of the system. They are ordered in three groups: resource availability, ecosystem vitality, and human welfare.

Experience has shown that decision makers learn to work with a RamCo-like DSS rather quickly, hence, that the logic behind the approach makes sense to them. The latter is essential for the acceptance of any Decision Support System. However, it is only the first hurdle to take. The next one is to convince the decision maker to spend the time required to uncover the many possibilities offered by the interactive and explorative approach promoted by the DSS. Because only an intensive interaction between the system and the decision maker will contribute to the design and implementation of actions to pilot the real world system past the worst and hopefully towards the most desirable future possible.
7. Discussion and conclusions

Despite the fact that we end the previous sections with a statement on the tiptoe of expectations, we would not like to conclude this paper without a number of warnings and points for further research and discussion.

Tobler warned his readers in 1979 that traditional cellular automata models were too simple to be useful for modelling real geographical systems. Ever since, spatial scientists including us have worked very hard on this problem and have been able to make good progress in applying ever more complex models to real world applications. Such has been the progress made that one of the models discussed in this paper, The Environment Explorer, is applied to analyse and evaluate policy options that soon will become part of the next National Plan, restraining the main spatial developments in the Netherlands for the period 2005-2030. Cellular automata models, simple systems as they may be, have surprised many an analyst in the ease with which they generate very complex forms. In the ease as well with which they can be made to mimic observed morphogenesis in spatial systems. Yet, in order to get more confidence in their capabilities, what is required at this moment are more in-depth empirical proofs of the results produced. Also, better theoretical foundations, anchored deeply in the classic spatial theories or geo-statistics, for defining the transition rules that drive their dynamics. And finally, more appropriate tools to calibrate them to specific cases and applications. Hence, a lot of work for many a scientist, both field workers and theoreticians is required and is ongoing.

In this paper we have also discussed how cellular automata models can be the core of successful integrated spatial models. The need for integrated models is strongly advocated in disciplines such as Integrated Assessment (see for example: Gough et al., 1998). Model integration is a deep scientific problem but even so a pragmatic multi-criteria multi-objective problem. Model integration requires dealing with end-use aspects: what is appropriate to be integrated in view of the intended use, the scientific aspect: what can and cannot be integrated on scientific grounds; and the technical aspects: how will the integrated model be assembled and run. Yet, and despite the fact that the terms ‘integral model’ and ‘integrated model’ are used all over, there are very few recipes or procedures for model integration available from the scientific literature. Thus, model integration seems more an art than a science at this moment.

Integrated spatial models can be appropriate tools for tackling integrated spatial policy problems. However, policy models come with a set of requirements of their own distinguishing them rather clearly from research models. Policy makers are most served by models in which the time horizon, the spatial and the temporal resolution are policy problem oriented and not so much process oriented as in research models. They need adequate rather than accurate representations of the processes modelled and sketchy but integral rather than in depth and sectoral models. While research models are as complicated as necessary and scientifically innovative, the policy maker is better served with an instrument that is as simple as possible and scientifically proven. If these differences are ignored in the integration process, a large-scale sluggish model will be the result that is not adapted to the needs and expectations of its end-user. Clearly, a fast, interactive model equipped with a graphical interface will do much better. Finally, in policy making models serve more purposes than analysis alone. Their function as
tools enabling discussion, communication, experimenting and learning is just as important.

A model will only serve the policy end-user if it is handed to him in a format that enables him to work with it. In Decision Support Systems, models are supplemented with sets of tools to structure and carry out the analysis in a manner that makes intuitive sense to the policy maker. One of the crucial elements in the DSS is the user-interface. It is a very essential element in bridging the gap between the world of the policy maker and that of the model developers and computer specialists. It should hide the technical complexity of the information system without reducing its flexibility and transparency. Attaining the level of user-friendliness and flexibility that policy-makers seem to desire is a very big challenge for computer scientists, model developers and domain specialists. Experience has learned that it is a prerequisite for the success of any Decision Support System to involve the intended end-user in the development process right from the beginning. For the complex decision domains discussed in this paper the latter is of paramount importance. Even then, it is extremely difficult to built systems that have the level of interactivity, flexibility and the fast response time wanted, the user-friendliness, simplicity and the transparency desired, and, at the same time, the level of accuracy and certainty expected. A lot more innovative research, design and implementation work will need to be carried out to get to this point if ever we do. For certain, the demand for the kind of instruments is real. Policy questions have reached a level of complexity that can no longer be dealt with by politicians alone. High-level technicians are playing an ever-increasing role, and, the revolution in hardware and software technologies has equipped them with very powerful multi-media calculators.

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