Xplorah, A multi-scale integrated land use model

Hedwig Van Delden

E. R. Gutiérrez

Jasper Van Vliet

Jelle Hurkens

iEMSs 2008: International Congress on Environmental Modelling and Software
Integrating Sciences and Information Technology for Environmental Assessment and Decision Making
4th Biennial Meeting of iEMSs, http://www.iemss.org/iemss2008/index.php?n=Main.Proceedings
M. Sànchez-Marrè, J. Béjar, J. Comas, A. Rizzoli and G. Guariso (Eds.)
International Environmental Modelling and Software Society (iEMSs), 2008

Xplorah, A multi-scale integrated land use model

H. van Delden[a], E.R. Gutiérrez[b], J. van Vliet[a] and J. Hurkens[a]

[a] *Research Institute for Knowledge Systems, P.O. Box 463, 6200 AL Maastricht, The Netherlands (hvdelden/jvanvliet/jhurkens@riks.nl)*
[b] *Graduate School of Planning, University of Puerto Rico, P.O. Box 23354, San Juan, Puerto Rico (eliasgutierrez@yahoo.com)*

Abstract: Processes of land use change and their drivers take place at different spatial and temporal scales. The fact that these processes are very often interacting with each other throughout these scales provides major challenges to modellers. Xplorah is a tailor made Spatial Decision Support System for the three major islands of Puerto Rico. It aims to assess the impact of different scenarios on the development of the island. The system encompasses an integrated set of dynamically linked models working at different scales and incorporating knowledge from numerous disciplines. This paper describes the integrated model as well as its individual components. It focuses on the integration between the socio-economic and bio-physical processes and models, and discusses how the system can be used to assess the impact of different policies relevant to and defined by the user of the system, Puerto Rico's Planning Board.

Keywords: Spatial Decision Support System; Impact Assessment; Land use modelling, Model integration, Integrated spatial planning.

1. INTRODUCTION

Puerto Rico is a very special island because of its vibrant cultural life, the architecture of its towns, the remnants of its past, and its natural marvels: coral reefs, beaches, caves, and tropical forests. With a population just below 4 million living on an area less than 10,000 km^2, it is also a densely populated place (Engelen, 2003).
Puerto Rico has many of the generic problems that islands, and small islands in particular, experience: an open and relatively small economy, a rugged landscape with a concentration of activities in the coastal zone, fragmentation and loss of high quality land, pressure on the coastal wetlands, deforestation, flooding, pollution, scarcity of drinking water, etc. Moreover, the island is located on the path of many tropical storms entering the Caribbean seas. Some of these gain hurricane force and cause tremendous damage. If global warming causes an increase in both the intensity and the frequency of tropical storms, Puerto Rico should be prepared and implement integrated spatial planning practices to minimise the potential damages (Engelen, 2003).

The Xplorah Spatial Decision Support System (SDSS) has been developed with the aim to support integrated decision making on the island of Puerto Rico. It allows the user to explore the impact of a wide range of scenarios –consisting of a combination of external factors and policy options– on policy-relevant indicators by simulating future developments in the region over a time span of 20 to 30 years. It comprises an integrated model in which the processes at stake on the island are incorporated.
The main aim of Xplorah is to assist policy makers in (1) understanding the important processes in the region and their interaction, (2) indicate current or future problems on the island, (3) assess the impact of possible policy measures, (4) evaluate the different alternatives and (5) stimulate discussion and improve communication between the different actors involved in the decision-making process.

Rather than focusing on all elements that are important in the initialisation, design, development and implementation process of the Xplorah SDSS, we limit ourselves in this paper to describing the different elements of the system, their interaction and the way it can be used for impact assessment studies. More insight in the development process of integrated spatial decision support systems as well as their practical applications and use can be obtained from Hurkens et al. (2008), Van Delden et al. (2007), Rutledge et al. (2007) and Van Delden and Engelen (2006).

2. AN INTEGRATED MODEL

Throughout the design and development of the Xplorah SDSS integration has always played a crucial role: integration between disciplines, integration between scales and integration between (scientific) knowledge, information technology and policy-making.

Where sectoral models often focus on the detailed representation of the processes at stake, Xplorah aims to create dynamic feedback loops between the different sectoral models included. For this reason it uses, to the extent possible, existing disciplinary models. For the integration Xplorah makes use of the GEONAMICA software environment that is specifically designed for the development of spatial decision support systems that integrate a number of non-spatial and spatially explicit models (Hurkens et al., 2008).

Due to the non-linear character of the model and the high degree of linkage among the variables, the set of equations cannot be solved analytically; rather their simultaneous solution is computed numerically in discrete time steps. The temporal resolution of the system is a year, its temporal horizon 2030.

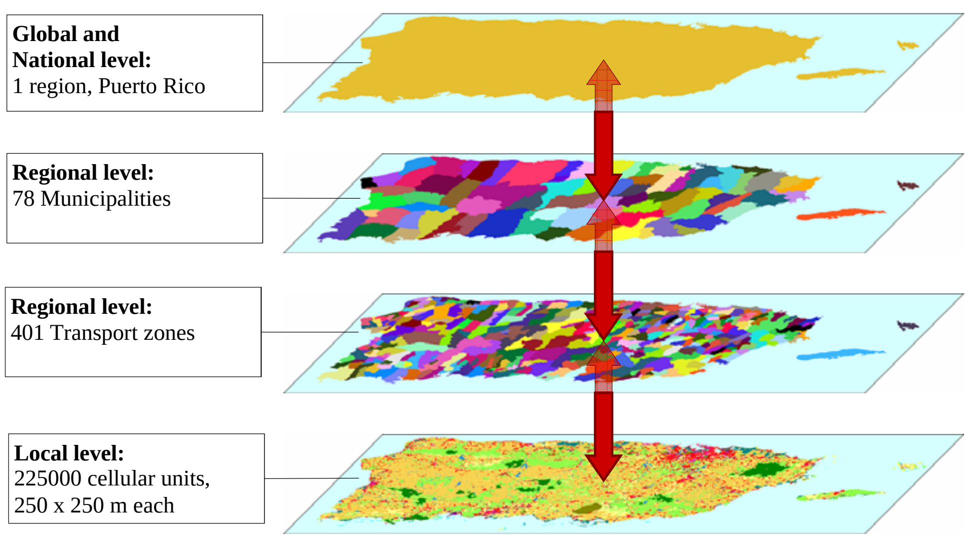

Figure 1. Different interlinked spatial scales in the Xplorah SDSS.

The models that are incorporated in Xplorah simulate activities that take place at four spatial scales: global, national, regional and local. At the global level, climate change has an important impact on the national economy by influencing tourism, agriculture and the demolishment and reconstruction of buildings as a consequence of hurricanes and changes in rainfall and temperature.
A national macro-economic model is tied with an age-cohort model that simulates structural demographic changes and population levels. This model incorporates immigration patterns and provides the labour force supply. Economic conditions, in turn, have an impact on migration and mortality rates.
At the regional level, socio-economic changes take place based on the relative attractivity of regions and the costs required to travel from one region to another. These costs are provided by the transport model that uses information from the regional and local models to

generate trips. This provides the basis for the distribution of national growth as well as migration of jobs and people over regions.

Furthermore, on the local level, land use demands from the regional model are allocated in cells based on several elements including local accessibility, physical suitability, zoning regulations and the attraction and repulsion between different land use functions. The local bio-physical and socio-economic characteristics, finally, feed back into the attractivity at the regional level.

The different components and their interactions are schematised in the system diagram of the Xplorah SDSS in Figure 2. The processes modelled in the components are described in the paragraphs below.

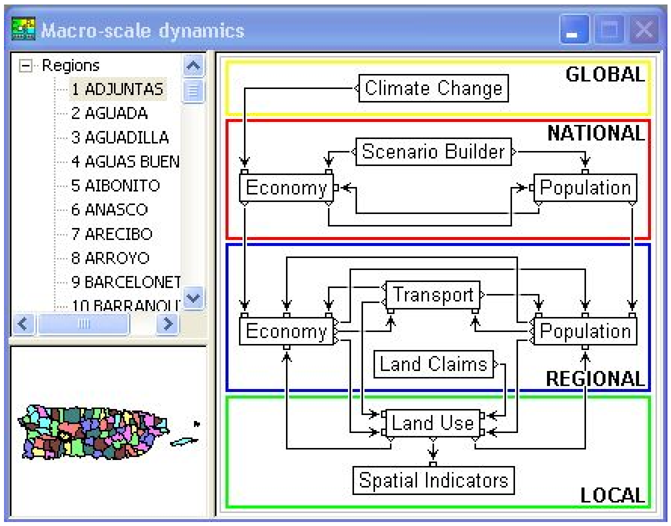

Figure 2. System diagram of the Xplorah SDSS.

2. 1 Models at global and national level

At the highest levels of the model there are components representing climate change, macro-economics and demographics. We have incorporated the impact of (global) climate change as a set of relations that impact different sectors of the economy on the island. At national level models to describe the macro-economics and the demographics are closely linked through mutual feedback loops. Part of the output of these models is used as a driver for the regional models: national population and jobs in main economic sectors.

The climate sub-system consists of a set of linked relations expressing the change in time of temperature and its effects on precipitation, storm frequency and, secondarily, external demands for services and products from Puerto Rico. This component is not a true model, rather a set of linked hypotheses representing current knowledge and assumptions, which the user is free to change. Clearly, this component is a very strong simplification of reality. However, and in the absence of more elaborate models, this representation has the great advantage of enabling to test hypotheses in a relatively straightforward manner.

The economy of Puerto Rico is modelled by means of a macro-economic model (Gutiérrez, 2007) linked to an input-output model, forecasting all final demand components and employment by sectors. In combination these models describe the economic situation on the island over time and also show the impact of changes on the main sectors of the economy –agriculture, construction & mining, manufacturing, services and government– in various levels of detail. Growth in the economic sectors is the result of changes in the final demands for goods of these sectors. On a yearly basis, the final demands of the input-output model change in response to information generated by the macro-economic model: aggregate demand changes in response to an increased demand for consumption driven by changes in population figures, the population's buying power, public and private investment, and exports. Puerto Rico is a very open economy. Thus, changes do take place as a result of external and policy drivers captured in scenarios. Exports change in response

to changes in the US economy and other markets. Furthermore, output from the climate sub-system can influence certain sectors, such as tourism, agriculture and construction.
In turn, the outputs of the macro-economic system interact with demographic trends. Jointly, these forces influence changes in sectoral production. The latter affects the regional activity (jobs in the main economic sectors and population) as well as the demands for land at the local, cellular level.

An age-cohort model generates population figures at yearly intervals by sex and age, on the basis of births, deaths and net migration. Fertility, mortality, and net migration rates are each assumed to be characterized by trends. In addition, it includes features that capture the effects of changing economic conditions (as calculated by the macro-economic system). While the structural component represents the long-term underlying demographic trends, the economic component captures changes that may weigh in on demography due to changes in the wealth of the population. The economic component is particularly important in the case of migration, since the flow of migrants generally responds to changes in relative economic conditions. Initial birth, mortality, and migration rates are taken from US census statistics; number of births and deaths are provided by the Commonwealth Health Department. Migration rates are inferred from census data. All of these rates can be explored in their consequences on land uses, through scenarios entered by the user of the model.

2. 2 Models at regional level

At regional level three model components are incorporated: a spatial interaction model that distributes national totals for population and jobs over the municipalities, a transport model that represents the travel behaviour and calculates the main transport flows and distances between the different regions and a land use demand component that converts the regional levels of activity in different socio-economic sectors, expressed in number of jobs or people, to land use demands for the local model.
The first component of the regional model in Xplorah uses the 78 municipalities of the island as regions and provides information on population as well as the five main economic sectors. The migration of activity between regions uses the concept of a gravity or spatial interaction model (Fotheringham & O'Kelly, 1989). From the levels of activity in each region and the migration flows, we can derive the demand for activity in each region in the next time step. Moreover, the demand for activity also incorporates other factors, such as the national growth of activity, which is calculated by the national demographic and economics models. If we incorporate these three factors, the demand for activity can be derived from the inert activity in that region, the activity that migrates to that region and the national growth that ends up in that region.
The measure of distance that we use in the spatial interaction model is very important. In fact, it is the determining factor of this model for the accuracy with which migration flows can be modelled. We know from experience and literature –see for example Fotheringham, et al. (2000)– that Euclidian distance, or distance measures derived from this, are a relatively inappropriate measure of distance for modelling population migration. Modelled travel times provide much better results. For this reason we have incorporated a transport model that can calculate travel times based on activities, travel behaviour and the road network.

The transport model incorporated in Xplorah is based on a classical four step approach: production-attraction, distribution, modal split and assignment. Like the spatial-interaction model it works at regional level, although its regions are transportation zones. They are generally smaller than municipalities and their sizes depend on the activity that can be found within the zone. Since urban and rural areas have different characteristics and behaviour regarding transport, a classification of the urbanization level of the different transport zones is used throughout the model.
In its first step the model calculates the production of trips from each zone to each other zone based on the activity levels in each zone and the travel behaviour of different groups in society. This generation of trips is not uniform in space but varies with the degree of urbanisation. Over time the number of trips per unit of activity can also change, as the general level of mobility changes. Furthermore, the model accounts for car sharing and

cargo transport, where the first decreases the impact of trips on the network and the latter increases it since trucks use more space than regular cars.
In the distribution step, production and attraction levels in different zones will be linked together. In other words, it is decided which pairs of origins and destinations form trips. Actors select their destinations and their mode of transport as a function of the associated generalised costs. It takes time however for actors to change their behaviour and preferences. Therefore a major factor determining the selection of destinations and modes is the existing transport pattern. It is here where we have made a modification to the classical equilibrium based transport model in favour of a more dynamic approach. The result of the distribution step is an origin-destination matrix (OD-matrix) specifying trips for each transport motive.
In the modal split it is decided which trips are made by car or public transport based on the generalised costs of each decision. These generalised costs include travel distance, travel time, parking costs, toll costs and the aversion for one or the other mode. The latter includes the preference a lot a people have to go by car because of the freedom that it gives them. The travel time component is heavily determined by the congestion on the network and therefore this step requires a strong interaction with the assignment step.
In the assignment step, actors make decisions based on the same generalised costs as in the modal split step. This time however they aim to find the cheapest route from A to B and therefore need information from the transport network. Their behaviour and route selection has a direct impact on the intensity and congestion of the road network and might influence others to take a different route. The result of the assignment step is the allocation of all trips over the road network and the calculation of the intensity, congestion and travel speed on each road element.

We have stated above that the levels of activity form a restriction on the land use demands of the local model. To be more precise, the demand for activity is converted to a number of cells that needs to be allocated in a region. Cell-productivity expresses the amount of activity in a sector that is located in one cell. The average cell-productivity in each region is modelled differently for economic and population sectors and for natural sectors. In the latter case, the activity is defined in terms of surface area, so the productivity is equal to the surface area of one cell. In the former case, the activity is expressed in terms of the number of jobs or people. For these sectors the average cell-productivity in a region will rise as the total level of activity in that sector rises, even if there is enough space for the sector to expand. If the amount of space available is also a critical factor, the average cell-productivity will rise even more. We term this the crowding effect.
We can distinguish two growth factors that can cause a rise in the average cell-productivity in a sector and region, complemented by the crowding effect and a growth coefficient. These five factors are:

- The growth in the level of activity. This is defined as the ratio of the demand for activity and the current level of activity.
- Changing conditions at the local level related to the physical suitability of locations, the zoning regulations, the accessibility and the neighbourhood effect.

The number of cells that needs to be allocated to each sector in each region is equal to the ratio of the demand for activity and the average cell-productivity.

2. 3 Models at local level

At the local level, the main island of Puerto Rico is subdivided in 225,000 cellular parcels of 6.25 ha each (250 x 250 m cells). Each cell represents the dominant land use of the cell. In Xplorah, 19 land use categories are incorporated of which residential, industry, trade & services, agriculture, forest and natural are the most important.
A cellular automaton based land use model is used to determine the state of a cell within the overall growth for each of the 78 municipalities calculated by the regional model (White and Engelen, 1993, 1997). Changes in land use at the local level are driven by four important factors that determine the potential for each location for each actor (see also Figure 3):

1. Physical suitability, represented by one map per land use function modelled. The term suitability is used here to describe the degree to which a cell is fit to support a particular land use function and its associated economic or residential activity.

2. Zoning or institutional suitability, represented by one map per land use function modelled. For different planning periods the map specifies which cells can and cannot be taken in by the particular land use.
3. The accessibility, represented by one map per land use function modelled. Accessibility is an expression of the ease with which an activity can fulfil its needs for transportation and mobility in a particular cell, based on the transportation system.
4. Dynamic impact of land uses in the area immediately surrounding a location. For each land use function, a set of spatial interaction rules determines the degree to which it is attracted to, or repelled by, the other functions present in its surroundings; a 196 cell neighbourhood.

If the potential is high enough, the function will try to occupy the location, if not, it will look for more attractive places. New activities and land uses invading a neighbourhood over time will thus change its attractiveness for activities already present and others searching for space. This process constitutes the highly non-linear character of this model.

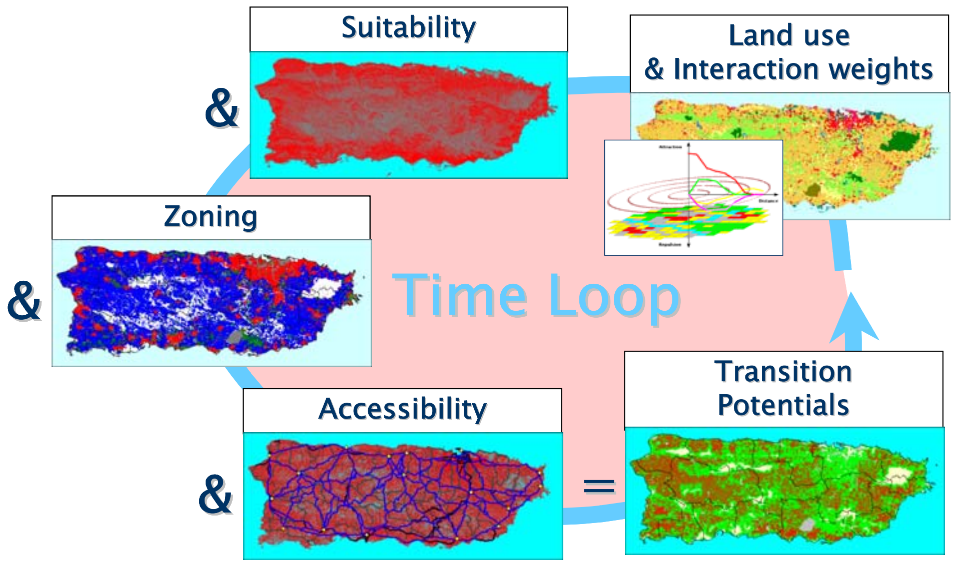

Figure 3. Schematic representation of the model at local level.

3. PROVIDING SUPPORT TO IMPACT ASSESSMENT

For any system to provide support to impact assessment it has to provide the possibility to enter the crucial driving forces on the input side and show the impacts on relevant indicators on the output side. The Xplorah SDSS is designed in such a way that scenarios can be set up that include a combination of external factors and policy options, which can be entered or changed by the user. External factors included in Xplorah are amongst others climate change; macro-economic drivers like interest rates, oil prices, growth rates in the US and money transfers from the US to Puerto Rico; and demographic drivers like fertility, migration and mortality rates. Xplorah also includes a wide range of policy options such as government consumption, public investment, development of public housing units, road prices, zoning regulations and construction of infrastructure.

To provide support to the decision making process the system is equipped with several policy relevant indicators. An indicator in this context is a measure to make a particular phenomenon perceptible that is not –or at least not immediately– detectable. On the other hand, indicators can also be set up to verify legislative guidelines or policy goals. Indicators are in fact small sub-models that generally simplify model results in order to make complex phenomena quantifiable in such a manner that communication is either enabled or promoted. Indicators in Xplorah are provided as (non spatial) numerical values and as maps with a resolution similar to that of the local model (250 x 250 m). Examples of numerical indicators are GDP in main economic sectors, proportion of population employed, total population, number of jobs per municipality and housing stock. Examples of spatial indicators are urban clusters, distance from residential locations to work locations, flood damage and habitat fragmentation.

By running the model under different scenarios, future developments of the island can be explored and evaluated using a number of selected indicators. Different alternatives can either be compared against each other, or against a 'baseline scenario' that assumes similar behaviour in the future as in the past. Furthermore also the temporal developments within a scenario can be investigated and compared to initial conditions or any other selected point in time.

4. CONCLUSIONS AND RECOMMENDATIONS

Real world problems and processes are not limited to a specific sector or discipline, but are interacting with each other throughout different domains. Models attempting to represent the real-world system should therefore incorporate the different disciplines and their dynamic feedback loops. To be able to represent real-world phenomena in their true complexity, the Xplorah SDSS has been equipped with a fully dynamic model that integrates climate, economy, demography, transport and land use.

Spatial Decision Support Systems that comprise an integrated model are able to assess the impact of (sectoral) policy options on a wide range of indicators. Xplorah is equipped with a number of policy options and its strong feedback loops between the different sectors allow the user to assess the impact of a policy option not only on his or her own discipline, but also on the other disciplines incorporated. Understanding those impacts can prevent the occurrence of unexpected and unwanted side-effects after the implementation of new policies.

In the development of an SDSS it is important to create links between user-relevant drivers and model inputs as well as between model outputs and user-relevant indicators. Moreover, the user should have the possibility to set up a scenario that consists of (a combination of) external factors and policy options, since this facilitates the creation of different scenario alternatives and the assessment of their impacts.

Xplorah has been developed in an iterative manner. Initially it started with the local land use model and over time a range of components has been integrated into the system. During such a development process it is very important to evaluate the system against its required capabilities for impact assessment. At present, the main points for attention are:

- The climate component incorporated in the system consists of simple and direct relations between a few variables and is as such a very strong simplification of reality. In more elaborate versions of the model, the relations used could be replaced by dedicated sub-models describing the underlying processes at deeper levels.
  Moreover, the natural sub-system is represented in a very limited manner as a measure of the physical suitability of the land for receiving the activities included in the model. The climate sub-system could be complemented with a natural sub-system including models describing the dynamics of natural systems such as forests, coral reefs, mangroves, river systems, beaches, etc.
- The input-output model describes the economy of the island as a set of linear equations. This approach has the advantage of ensuring that the output of the economic model is internally consistent. In addition, it captures the interdependencies between economic sectors and thus represents well the multiplier effects by which changes in one sector propagate through the entire economy. On the other hand, the method is based on an assumption of constant technical coefficients, so that changes in the underlying structure of the economy, due to, for example, technological innovations, import substitution, or factor substitutions in response to changes in relative prices, are not represented. This is not a problem for short run situations, but becomes much more of a concern when the modelling period runs to several decades (which is the case in the present

model). Ideally, in the context of the present model, the technical coefficients would evolve in response to substitution and changes in productivity generated by the local model.

At present, the Xplorah system is being implemented in Puerto Rico's Planning Board. A group of around 50 staff members, ranging from technicians and middle managers to executives, are following an extensive training course to become expert users in the system. During this implementation phase the system is also evaluated on its capability to provide support to actual planning problems on the island. In this process it will be a challenge to create awareness not only on the capabilities of the system, but also on its limitations. The system helps to understand how different processes are related and explores the impact of different external factors and policy options. Xplorah, like any model, is however a simplification of reality and will not give exact predictions of the future. Its strength is in *supporting* learning, analysis and communication, not in *making decisions*. The responsibility of the latter lies with the decision-makers.
We expect that the current phase will provide some important recommendations for the further development of the system to improve its usefulness as well as its usability.

REFERENCES

Engelen, G., Xplorah, The Spatial Decision Support System for Puerto Rico. Brochure, 2003.

Fotheringham, A.S. and M.E. O'Kelly, Spatial interaction models. Dordrecht, The Netherlands, Kluwer, 1989.

Fotheringham, A.S., T. Champion, C. Wymer, M. Coombes, Measuring Destination Attractivity: A Migration Example. International Journal of Population Geography 6: 391-421, John Wiley & Sons, 2000.

Gutiérrez, E.R., Long-term View of the Commonwealth of Puerto Rico's Socio-Economic Environment: Planning Context for Corporate Decisions. Draft for discussion, 2007.

Hurkens, J., B.M. Hahn and H. van Delden (this conference). Using the Geonamica® software environment for integrated dynamic spatial modelling. In: M. Sànchez-Marrè, J. Béjar, J. Comas, A. Rizzoli and G. Guariso (Eds.) Proceedings of the iEMSs Fourth Biennial Meeting: "Integrating Sciences and Information Technology for Environmental Assessment and Decision Making". International Environmental Modelling and Software Society, Barcelona, Spain, 2008.

Rutledge, D., McDonald, G., Cameron, M., McBride, G., Poot, J., Scrimgeour, F., Price, R., Phyn, D., van Delden, H., Huser, B., Small, B., Wedderburn, L. & Fenton, T., Development of Spatial Decision Support Systems to Support Long-term, Integrated Planning. In: Oxley, L. and Kulasiri, D. (eds) MODSIM 2007 International Congress on Modelling and Simulation, volume December 2007, p.308-314, Modelling and Simulation Society of Australia and New Zealand, ISBN 978-0-9758400-4-7

Van Delden, H., P. Luja and G. Engelen, Integration of multi-scale dynamic spatial models of socio-economic and physical processes for river basin management. Environmental Modelling and Software, 22(2), 223-238, 2007.

Van Delden, H. and G. Engelen, Combining participatory approaches and modelling: lessons from two practical cases of policy support. In: Voinov, A., Jakeman, A.J., Rizzoli, A.E. (eds). Proceedings of the iEMSs Third Biennial Meeting: "Summit on Environmental Modelling and Software". International Environmental Modelling and Software Society, Burlington, USA, July 2006.

White, R. and G. Engelen, Cellular Automata and Fractal Urban Form: a Cellular Modelling Approach to the Evolution of Urban Land use Patterns. Environment and Planning A, 25, 1175-1199, 1993.

White R. and G. Engelen, Cellular Automata as the Basis of Integrated Dynamic Regional Modelling. Environment and Planning B, 24, 235-246, 1997.