

Please cite as:

Van Delden, H., Escudero, J.C., Uljee, I., Engelen, G., 2005. 'METRONAMICA: A dynamic spatial land use model applied to Vitoria-Gasteiz'. Virtual Seminar of the MILES Project. Centro de Estudios Ambientales, Vitoria-Gasteiz.

METRONAMICA: A dynamic spatial land use model applied to Vitoria-Gasteiz

Hedwig van Delden¹, Juan Carlos Escudero², Inge Uljee¹ and Guy Engelen^{1,3}

¹Research Institute for Knowledge Systems (RIKS)

²Environmental Studies Centre of Vitoria-Gasteiz

³Flemish Institute for Technological Research (VITO)

The METRONAMICA model and its tools

The primary goal of METRONAMICA is to explore the effects of (alternative) policy options on the quality of the socio-economic and physical environment and, with this information at hand, to stimulate and facilitate awareness building, learning, and discussion, prior to decision-making. To this end, the system combines autonomous developments with policy-induced changes to form integral pictures of possible futures for the area modelled and evaluates their relative value on the basis of social, economic and ecological criteria. It does not seek to optimise the separate economic, ecological and social dimensions, rather to maximise the whole. Although this means losing some detail, the benefit of the approach is the strong integrative and interactive nature of the resulting system, in which highly dynamic, autonomous processes play a key role.

The motor driving the spatial changes in METRONAMICA is fuelled by economic and demographic developments: supply and demand in both qualitative and quantitative terms. These processes operate at different spatial scales and are thus represented in the model. In fact, these dynamics are very much represented as the competitive reality of 'survival of the fittest': it is the function that is most powerful and that generates the highest added value per unit of area that will be most successful in claiming parcels of land. Similarly, it is the region that offers the most attractive alternative for economic and residential activity that will attract most businesses and residents. Government has the task of safeguarding collective interests, including protection of the economically weak, the social values, the open space and the natural assets in general. The actual and the intended policy actions to counter the initiatives of the 'free market' players can be entered into METRONAMICA by means of zoning maps acting as constraints upon the autonomous dynamics of the system.

Models coupled at different geographical levels

The core component of METRONAMICA is an explicitly dynamic land use-transportation model applied to the full territory of the area modelled. In order to represent the processes that make and change the spatial configuration of the area, it features a layered model representing processes operating at three geographical levels: the global (1 region, typically representing a group of countries, one country or an administrative or physical region within a country), the regional (n administrative regions, typically representing NUTS2, NUTS3 or NUTS4 regions) and the local (N cellular units).

For Vitoria-Gasteiz a simplified version of METRONAMICA has been applied –METRONAMICA SL– that comprises the global and the local model and from which the regional model is omitted (see Figure 1).

At the *global level*, the scale of the entire modelled area, the model integrates figures taken from economic, demographic and environmental growth scenarios considering developments in the area in the context of the region, the country, Europe and the world beyond and prepared by planning agencies, stakeholder groups, and/or others. From these, growth figures for the different land use functions are derived and entered in the model as global trend lines.

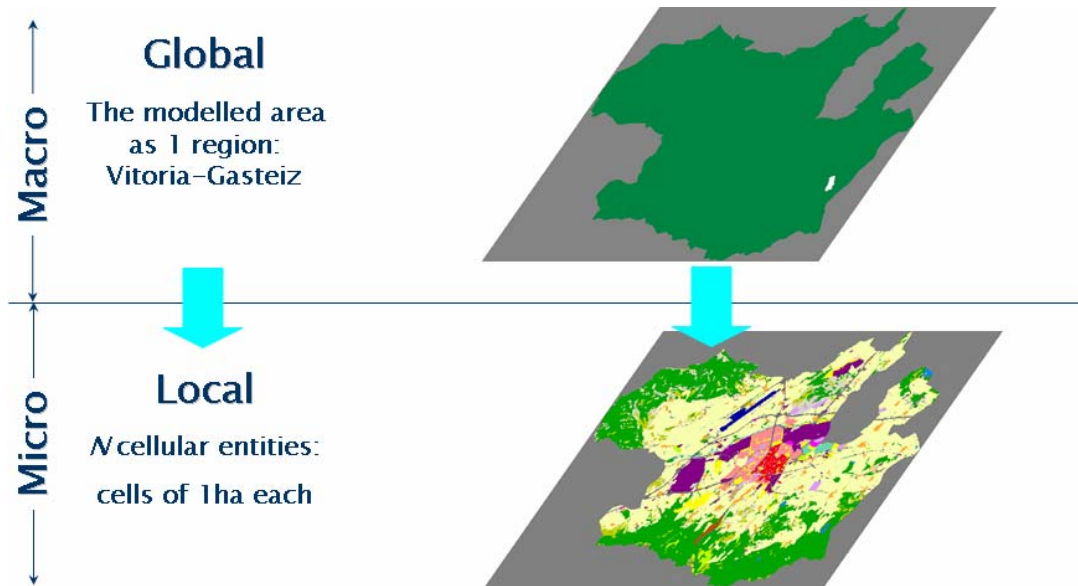


Figure 1: METRONAMICA SL represents processes at two spatial levels: global and local (Application of Vitoria-Gasteiz).

At the *local level* the detailed allocation of economic activities and people is modelled by means of a Cellular Automata based land use model (Coullelis, 1985; White and Engelen, 1993, 1997; Batty and Xie, 1994; Engelen et al., 1995). To that effect, the modelled area is represented as a mosaic of grid cells typically representing a parcel of land covering, depending of the type of application and the desired spatial detail, anything from $\frac{1}{4}$ ha to 1 km^2 (1 ha for Vitoria-Gasteiz). Each cell is modelled dynamically and together the cells constitute the changing land use pattern of the country. Land use is classified in a maximum (software-technical) of 32 categories, subdivided in ‘features states’ (fixed land uses that do not change dynamically), ‘function states’ (change dynamically as the result of the local and the regional dynamics) and ‘vacant states’ (change dynamically due to the local dynamics only). The land use function states are by all means the most important land uses in the model and are chosen with a view to guarantee as much as possible a one-to-one relation with the economic and residential categories at the regional level. In principle, it is the relative attractiveness of a cell as viewed by a particular spatial agent, as well as the local constraints and opportunities that cause cells to change from one type of land use to another. This model is driven by the demands for land for the total area of Vitoria-Gasteiz generated at the global level. Four elements determine whether a piece of land (each cell) is taken in by a particular land use function or not (see Figure 2):

1. The physical *suitability*. Suitability is represented in the model 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 the associated economic or residential

activity for a particular activity. It is a composite measure, prepared in a Geographical Information System (GIS), on the basis of factor maps determining the physical, ecological and environmental appropriateness of cells. Factors used are typically: elevation, soil quality and stability, agricultural capacity, air quality, noise pollution, etc.

2. The *zoning* or institutional suitability. Zoning too is characterized by one map per land use function. It is another composite measure based on master plans and planning documents available from the national or regional planning authorities including among others ecologically valuable and protected areas, protected cultural landscapes, buffer areas, etc. For three consecutive planning periods, to be determined by the user (example: 2000-2005, 2005-2015, and 2015-2030), the map specifies which cells can and cannot be taken in by the particular land use. For the analysis of policy and planning alternatives, it is of paramount

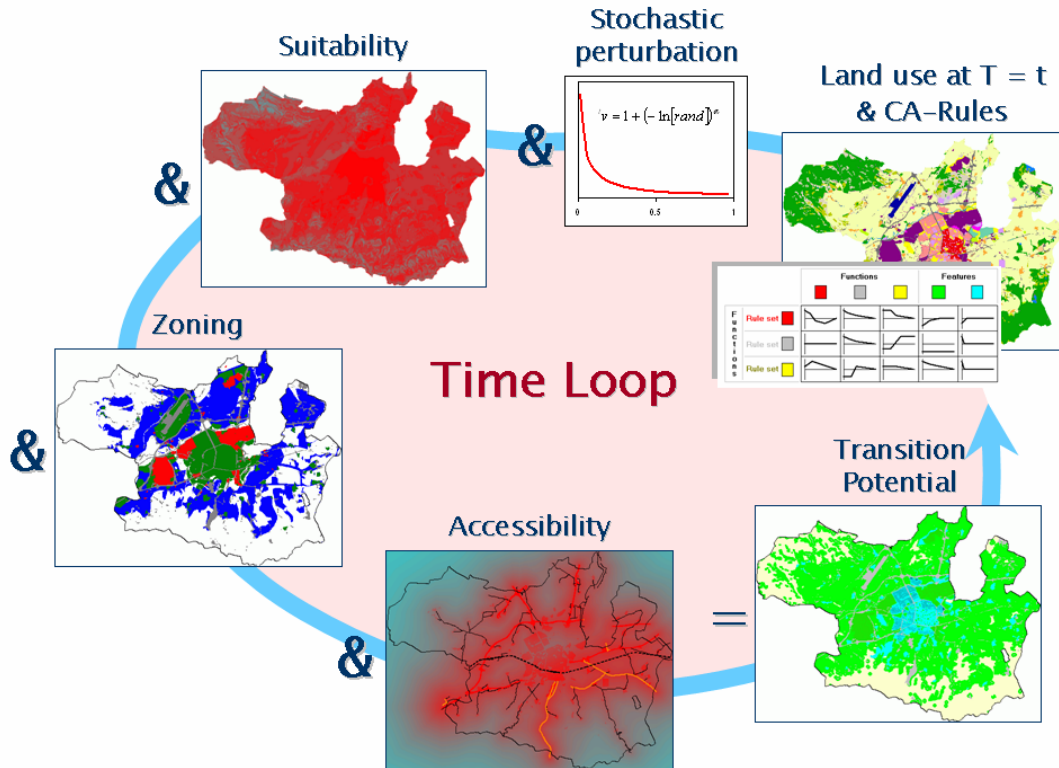


Figure 2: 4 elements: dynamics at the local level, suitability, zoning, and accessibility, determine the yearly land use changes that take place at the local level (Application Vitoria-Gasteiz, resolution is 1 ha)

importance that suitability and zoning can be handled separately. Zoning is a man made instrument for imposing constraints or stimulating particular trends, while suitability is most often a fact of life and an intrinsic quality of the area. Changing suitability requires usually an engineering action in the physical environment, such as altering slopes, filling in land, building infrastructures, etc., while changing zoning requires first of all an intervention in the legal and institutional environment.

3. The *accessibility*. The accessibility for each land use function is calculated in the model relative to the transportation system consisting of the railways and railway stations, the navigable waterways, and the road network. It is an expression of the ease with which an activity can fulfil its needs for transportation and mobility in a particular cell. It accounts for the distance of the cell to the nearest link or node on each of the infrastructure elements, the importance and quality of that link or node, and the needs for transportation of the particular activity or land use function.
4. The *dynamics at the local level*. While the above three elements are introduced in the model to determine the non-homogeneous nature of the physical space within which the land use

dynamics unfold, there is a fourth and important aspect, namely the dynamic impact of land uses in the area immediately surrounding a location. This is no longer the domain of abstract planning, rather that of the reality on the ground representing the fact that the presence of complementary or competing activities and desirable or repellent land uses is of great significance for the quality of that location and thus for its appeal to particular activities. For each location, each cell that is, the model assesses the quality of its neighbourhood: a circular area with a radius of 8 cells containing the 196 nearest cells. For each land use function, a set of rules determines the degree to which it is attracted to, or repelled by, the other functions present in the neighbourhood. The strength of the interactions as a function of the distance separating the different functions within the neighbourhood is articulated in these rules. If the attractiveness 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 explains the decay of a residential neighbourhood due to the invasion by industrial or commercial activities, as well as the gentrification and revival of decayed neighbourhoods initiated by the arrival of a new type of residents, or economic activities, few high quality functions like parks, exclusive office buildings, high-end condominiums, etc. The rules determining the interactions between the different functions –the inertia, the push and pull forces, and economies of scale– are defined as part of the calibration of this cellular automata model.

On the basis of these four elements, the model calculates for every simulation step the *transition potential* for each cell and function. In the course of time and until global demands are satisfied, cells will change to the land use function for which they have the highest transition potential. Consequently, the transition potentials reflect the pressures exerted on the land and thus constitute important information for those responsible for the design of sound spatial planning policies.

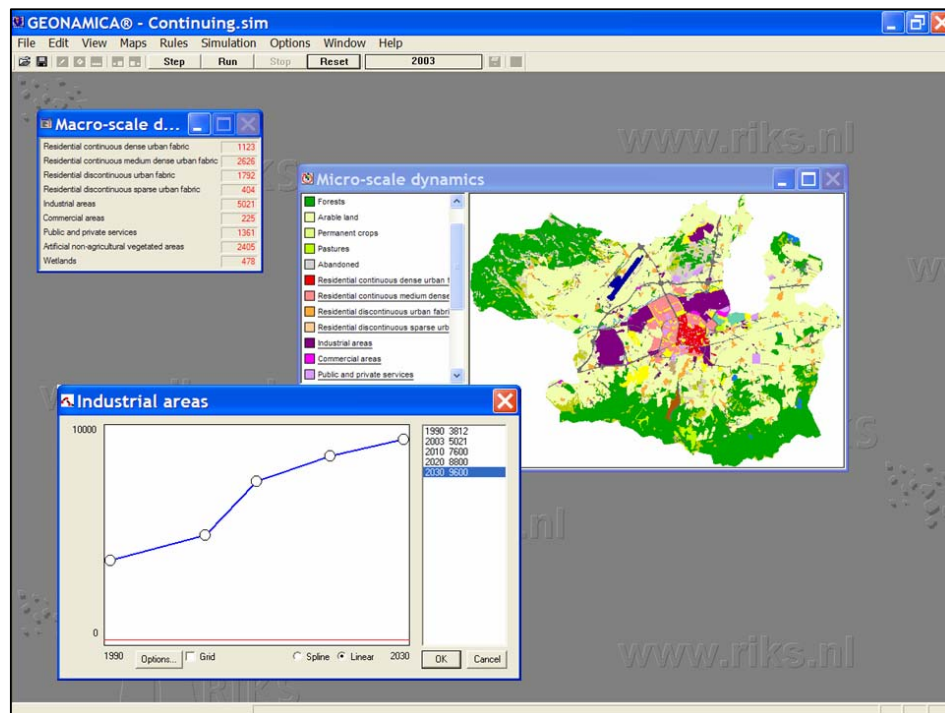


Figure 3: Part of the graphical user-interface of a METRONAMICA application. (Application Vitoria-Gasteiz at 1 ha resolution).

State variables and indicators

From the model description, it may be clear that METRONAMICA is driven by scenarios and other inputs at the global, and/or the local levels and that it generates output at the local level. Typically the model is run for a 30-year period into the future, but shorter or longer time intervals are possible too. Results are calculated and visualised on a yearly basis. At the local level the resulting new land use map is generated and presented for every simulated year (see Figure 3). In addition to these, and based on the regional and local state variables, the model calculates a number of spatial indicators expressing changes in the economic, social, or environmental status of the area modelled and the cellular entities. The indicators are specifically designed for the user based on algorithms provided by the user or developed on the basis of some 5 built-in generic spatial indicator algorithms performing operations on the state variables of the model. The latter type of indicators can be entered by the user through the user interface.

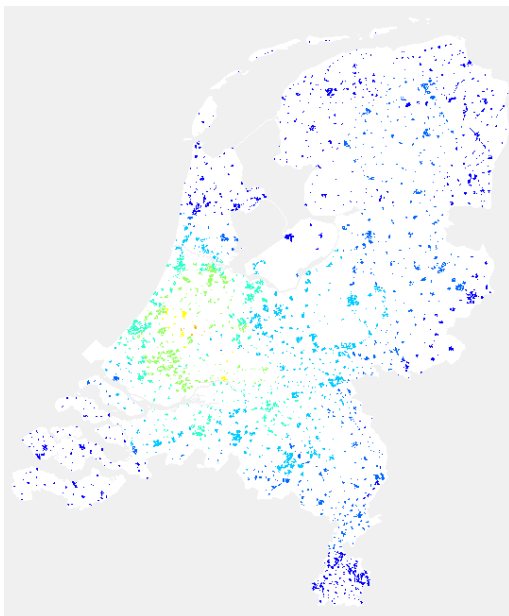


Figure 4: Job potential indicator showing the job potential from each residential cell

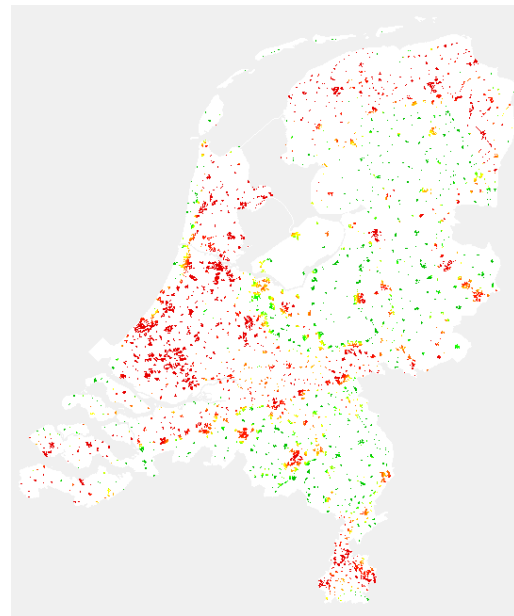


Figure 5: Access to green areas indicator showing the access to green areas from each residential cell

Indicators constitute important information relative to the merits of one or the other project, policy or strategy tried out with the model. Each indicator in itself is a more or less elaborate dynamic sub-model that may require specific ancillary information. Possible indicators include among others: job potential (economic, see Figure 4), access to green areas (social, see Figure 5), cost of land (economic), built-up area and soil sealing (social), open space (social), urban sprawl (environmental), recreational space per inhabitant (social), flooding risk (social), residential density (social), habitat fragmentation (environmental), and land degradation (environmental). Like the other state variables, indicators are calculated on a yearly basis and are available in METRONAMICA in the form of dynamic maps, time charts and numeric output.

The coming month (October 2005) indicators for the application of Vitoria-Gasteiz will be selected and implemented.

Setting-up and calibrating a new METRONAMICA application

In a number of past and ongoing projects, METRONAMICA has proven to be a generic and very flexible modelling framework which can be applied at a variety of spatial and temporal scales resolutions. No programming is required, to set-up and run a new application, but experience with GIS, spatial modelling, and the precise built-in models is very instrumental.

Calibration and validation of spatially-dynamic models is currently a very hot topic in the domain and much research effort is invested into it. The calibration of spatially-dynamic models is not a trivial problem. It is so because in principle every cell modelled represents at the least one state variable in the model. Thus, the models consist of tens of thousands, if not millions of dynamic equations. In practice however, a model will consist of a few types of equations only; usually a couple of dozen, but these equations are applied to and solved for thousands of spatial units. Hence an extremely rich behaviour can result from running the model. However, in the calibration process, the task is precisely to ensure that the model behaves in a realistic manner and is able of generating existing spatial patterns.

METRONAMICA SL has just recently been equipped with a semi-automatic calibration method. This method is currently available in a prototype version and could not be called 'fully automatic' method since user intervention is still required to use it. However, when used in semi-automatic mode, the method is very instrumental in speeding up the calibration of the local model: a good parameter set is found in a matter of hours, typically one or two nights, rather than one or two person-months of hard and tedious work by a specialist. Moreover, when started from an initial parameter set delivered by a specialist or taken from another application, the methods considerably outperform the specialist in the quality of the parameter and rule sets generated in a substantial manner. More information on the semi-automatic calibration method of METRONAMICA and METRONAMICA SL can be found in Van Loon (2004) and Hagen et al. (2005).

Tools

In order to construct, amend and evaluate integrated spatial strategies and scenarios, two tools are available, which are specifically designed to support the creation of input maps for METRONAMICA as well as to analyse its results: the OVERLAY-TOOL and the MAP COMPARISON KIT.

The OVERLAY-TOOL is an instrument geared at the creation of the suitability and zoning maps used at the local level of the model. It takes (factor) maps from a GIS as an input and combines them into a single composite map by weighing the relative importance of the information presented on the maps. The weights are set interactively through the manipulation of sliders on the screen. The composite map changes accordingly and instantly. The output can be exported straightforwardly into the METRONAMICA model or back into the GIS if desired.

Figure 6 shows the construction of a composite suitability map for industrial areas. Starting with a number a factor maps (A) a suitability map for each factor is constructed by giving a suitability value between 0 (light blue, unsuitable) and 10 (red, suitable) to each legend category. In this figure the slope map (B) is taken as an example. Based on the suitability for different slopes a slope-suitability map (C) for industrial areas is created. When this process is repeated for each (relevant) factor map all suitability maps can be combined into a composite

suitability map (D) for the chosen land use function by weighing the relative importance of the maps. Weighing of the maps can be done interactively by using the sliders (E).

A similar approach is followed in Figure 7 for the construction of zoning maps, in this example for discontinuous urban fabric. The list of factor maps can be found in A, the factor map for parks in B, the constructed zoning map based on the parks factor map in C (red indicates that the function is allowed at the location already at this moment, green that the location is open for construction from a certain moment $t=1$ in the future, blue that construction is allowed from a certain moment $t=2$ in the future, and white that construction is never allowed). Combining the zoning map for parks with the other zoning maps the composite zoning map for residential discontinuous sparse urban fabric can be found (D). For each land use function a composite zoning and a composite suitability map is used as input in METRONAMICA SL.

Besides the construction of input maps, the OVERLAY-TOOL is equally used for carrying out multi-criteria analysis on the spatial outputs of METRONAMICA and in particular on sets of indicator maps. The result of this analysis is one composite indicator map, or a series of such maps: one per year simulated, reflecting the concerns expressed in the weights and criteria selected. It thus is instrumental in evaluating the particular merits of policy options tried out in terms of their multi-faceted impacts, the spatial patterns generated, and the precise timing of events and developments.

The MAP COMPARISON KIT is an instrument enabling the pair-wise comparison of the many maps generated in particular runs of METRONAMICA, containing categorical data or data on a ratio or ordinal scale. It is an essential instrument for comparing and analysing the spatial effects of the alternatives generated. To that effect it is equipped with fuzzy set map comparison techniques capable of detecting qualitative similarities between maps (Power et al, 2001; Hagen, 2003), as well as other comparison tools and statistics such as the Kappa statistic (Monserud and Leemans, 1992).

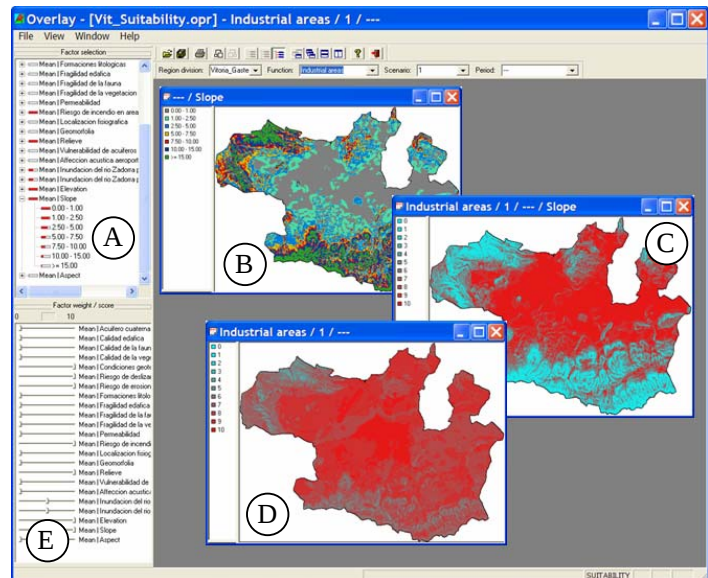


Figure 6: Construction of suitability maps with the OVERLAY-TOOL

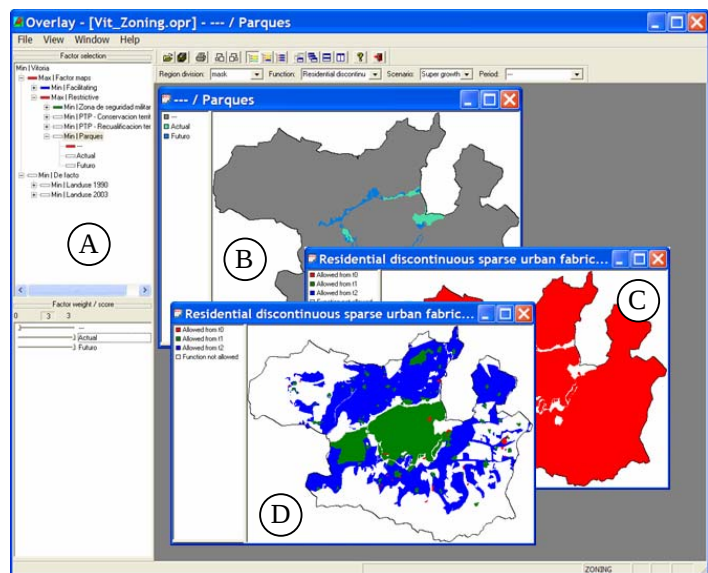


Figure 7: Construction of zoning maps with the OVERLAY-TOOL

The OVERLAY-TOOL and the MAP COMPARISON KIT are of particular use in interactive sessions with stakeholders and representatives of different planning departments as they focus the discussion on the importance of particular factors in the determination of the physical or institutional appropriateness of areas for one or the other use. Similarly, they enable a straightforward evaluation of alternatives designed and tried out in collaborative working sessions.

Conclusions and discussion

The METRONAMICA land use model integrates socio-economic and physical processes and provides an integrated view of the region of Vitoria-Gasteiz at a very detailed level (100 m grid cells). The system generates dynamic land use and land use change maps as well as dynamic indicator maps that are updated on a yearly basis until the end of the simulation period (2030). METRONAMICA allows an easy generation and assessment of future policies and development alternatives (ex-ante evaluation) and past spatial policies (ex-post evaluation) with the aim to support decisions made by planners and policy-makers. Through use in either individual sessions or stakeholder sessions it can help to improve the understanding of processes, stimulate discussion and facilitate communication.

References

- Batty M. and Y. Xie (1994). 'From cells to cities', *Environment and Planning B* 21: 31-48.
- Couclelis H. (1985). 'Cellular Worlds: A Framework for Modelling Micro-Macro Dynamics', *Environment and Planning A* 17: 585-596.
- Engelen G., R. White, I. Uljee and P. Drazan (1995). 'Using Cellular Automata for Integrated Modelling of Socio-environmental Systems', *Environmental monitoring and Assessment* 30: 203-214.
- Hagen-Zanker, A., J. van Loon, A. Maas, B. Straatman, T. de Nijs, and G. Engelen (2005). *Measuring performance of land use models, An evaluation framework for the calibration and validation of integrated land use models featuring cellular automata*. Proceedings of 14th European Colloquium on Theoretical and Quantitative Geography, Tomar, Portugal.
- Hagen, A. (2003). 'Fuzzy Set Approach to Assessing Similarity of Categorical Maps', *International Journal of Geographical Information Science* 17: 235-247.
- Monserud, R.A. and R. Leemans (1992). 'Comparing global vegetation maps with the Kappa statistic', *Ecological Modelling* 62: 275-293.
- Power, C., A. Simms and R. White (2001). 'Hierarchical Fuzzy Pattern Matching for the Regional Comparison of Land Use Maps', *International Journal of Geographical Information Science* 15: 77-100.
- Van Loon, J. (2004). 'Towards model-specific automatic calibration routines for the LeefOmgevingsVerkenner model', Thesis report, RIKS, Maastricht.
- White R. and G. Engelen (1997). 'Cellular Automata as the Basis of Integrated Dynamic Regional Modelling', *Environment and Planning B* 24: 235-246.
- White R. and G. Engelen (1993). '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.