The MOLAND model for urban and regional growth forecast

A tool for the definition of sustainable development paths

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Foreword

In the frame of the support to the conception, definition and implementation of European policies, the Land Management Unit of the Institute for Environment and Sustainability (Directorate General Joint Research Centre (DG-JRC) of the European Commission (EC)) is developing an integrated framework to evaluate and propose strategies for the sustainable management of the European territory. A key tool in this framework is the model for urban and regional growth forecast named MOLAND (Monitoring Land Use/Cover Dynamics) model. The model is part of an integrated methodology based on a set of spatial planning tools that can be used for assessing, monitoring and modelling the development of urban and regional environments.

The MOLAND urban and regional growth model is based on spatial dynamics systems called cellular automata. The model takes as input five types of digital maps, for the geographical area of interest: (a) actual land use types; (b) accessibility of the area to the transport network; (c) inherent suitability of the area for different land uses; (d) zoning status (i.e. legal constraints) of the area for different land uses;(e) socio-economic characteristics (e.g. population, income, production, employment) of the area.

Based on alternative spatial planning and policy scenarios, the model then predicts the likely future development of land use, for each year usually over the next ten to twenty-five years. In order to compare the alternative predicted land use maps produced by the model, in terms of the long-term sustainability of the input land use planning and management parameters, various indicators are computed and analysed. Predicted land use maps can therefore be used for natural hazards minimization and to identify structural and non-structural measures to be implemented in the frame of spatial planning policies. In this context, the analysis of urban areas and their development has particular relevance because of their complex relationships with factors related to floods, such as increased water runoff and accelerated stream response to precipitation, loss of natural flood retardation areas and others. Inappropriate regional and urban planning can exacerbate the negative effects of extreme hydrological processes. On the other hand, good land management and planning practices, including appropriate land use and development control in flood-prone areas, represent suitable non-structural solutions to minimise flood damage. The overall effects of these measures in terms of both sustainable development and flood defence can be quantified with the proposed integrated modeling approach.

CONTENT

1. INTRODUCTION

In the frame of the support to the conception, definition and implementation of European policies, the Land Management Unit of the Institute for Environment and Sustainability (Directorate General Joint Research Centre (DG-JRC) of the European Commission (EC)) is developing an integrated framework to evaluate and propose strategies for the sustainable management of the European territory.

A key tool in this framework is the model for urban and regional growth forecast named MOLAND (Monitoring Land Use/Cover Dynamics) model. The model is part of an integrated methodology based on a set of spatial planning tools that can be used for assessing, monitoring and modelling the development of urban and regional environments.

The MOLAND model aims to assist spatial planners and policy makers to analyse a wide range of spatial policies and their associated spatial patterns. The core of the modelling 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 (CA)-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 CA, these models are defined with larger neighbourhoods, and more cell-states representing socio-economic land-uses and natural land cover (see Barredo et al., 2003). 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.

The MOLAND Model has been developed in the frame of collaboration between the JRC and the RIKS Institute of Maastricht.

The MOLAND model is furthermore currently being integrated with the catchment based hydrological rainfall-runoff model LISFLOOD (De Roo et al., 2000) adapted for scenario modelling, flood forecasting and floodplain inundation modelling. One specific application of this integrated modelling scheme is to provide planning elements to prevent and mitigate the effects of extreme weather driven events such as flood and forest fires.

In this report we present a general picture of the MOLAND model framework for urban and regional growth forecast. Detailed technical descriptions are provided in Barredo et al. (2003; 2003b; 2004).

2. TOOLS FOR INTEGRATED PLANNING AND POLICY

Planners and policy makers face a difficult task. The world they must deal with is complex, interconnected, and ever changing. Urban planning, the design of policies for sustainable development and the integrated management of coastal zones and watersheds all pose the problem of dealing with systems in which natural and human factors are thoroughly intertwined. Understanding the processes that cause these systems to change and knowing their spatial ramifications is essential in preparing effective policies. Systems such as these must be understood and managed as dynamic entities, so that change is accommodated and system integrity maintained.

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, or evenly spread, or constant in time. The detailed location of activities is controlled by spatial interactions between mobile actors. The robustness and the success of a complex spatial system 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 about the expected outcomes 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. Models therefore should 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. Models should help exploring the relative merits of solutions. Thus they help in narrowing down the number of possible policy interventions, without making a predictive statement about the only or optimal solution.

In the course of the last decade, researchers have made considerable progress in improving the capabilities and usefulness of Geographical Information Systems (GIS) for management and policy purposes (Webster, 1993, 1994, Stillwell *et al.*, 1999), 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* (Jankowski 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 modelling in the preparation and evaluation of spatial policies. And, in the case of complex systems, 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.

In our effort to build practical instruments for urban and regional planning, we have developed integrated spatial simulation models and embedded them in Decision Support Systems. To this end we created new land-use simulation models, linked them to GIS, incorporated them in larger integrated models, and supplemented them with user-friendly 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. 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.

In the remainder of this report we will discuss the characteristics of this CA-based model and its use as the core element in integrated spatial models.

3. CELLULAR AUTOMATA MODEL AS THE CORE OF THE INTEGRATED MODEL

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 or 3-dimensional array is most practical;

- a cell *neighbourhood*. For flow and diffusion processes the 4 (*Von Neumann* neighbourhood) or 8 (*Moore* neighbourhood) 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.

Until recently, CA models raised 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).

The referenced literature furnished a detailed description of a generic constrained CA model and applied it to urban (Barredo et al., 2003b, 2004; White and Engelen, 1993, 1994, 1997; White *et al.* 1997) and regional (Engelen *et al.* 1993, 1995, 1996, 1997, 2000, 2002a) cases.

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 spaces that have heterogeneities at all levels of detail and are shaped by interaction processes that take place at different geographical scales. CA-based models aimed at representing geographical systems genuinely should accommodate for these aspects of reality. In this section we will discuss ways in which CA-based 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 CA 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 CA 'micro' models:

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. The MURBANDY model is another example.

2. A more satisfactory solution consists in using a 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. 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 and Engelen, 1997; White *et al*., 2000), and to a large coastal zone near Ujung Pandang in SW Sulawesi (Indonesia) (Uljee, *et al*., 1996; Kok *et al*., 1997).

3. Finally, a most powerful representation is obtained if a *regionalised dynamic macromodel* 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 CA model in an application for the Netherlands (De Nijs *et al*., 2001, Engelen *et al.*, 2002a), and the island state of Puerto Rico (Engelen et al., 2002b). The MOLAND model is a model of this kind. It will be further discussed later on in this report.

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 3.1).

The cellular space of CA is structurally not different from the cellular representation of space in raster GIS: they both are essentially a grid cell partitioning 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.

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:

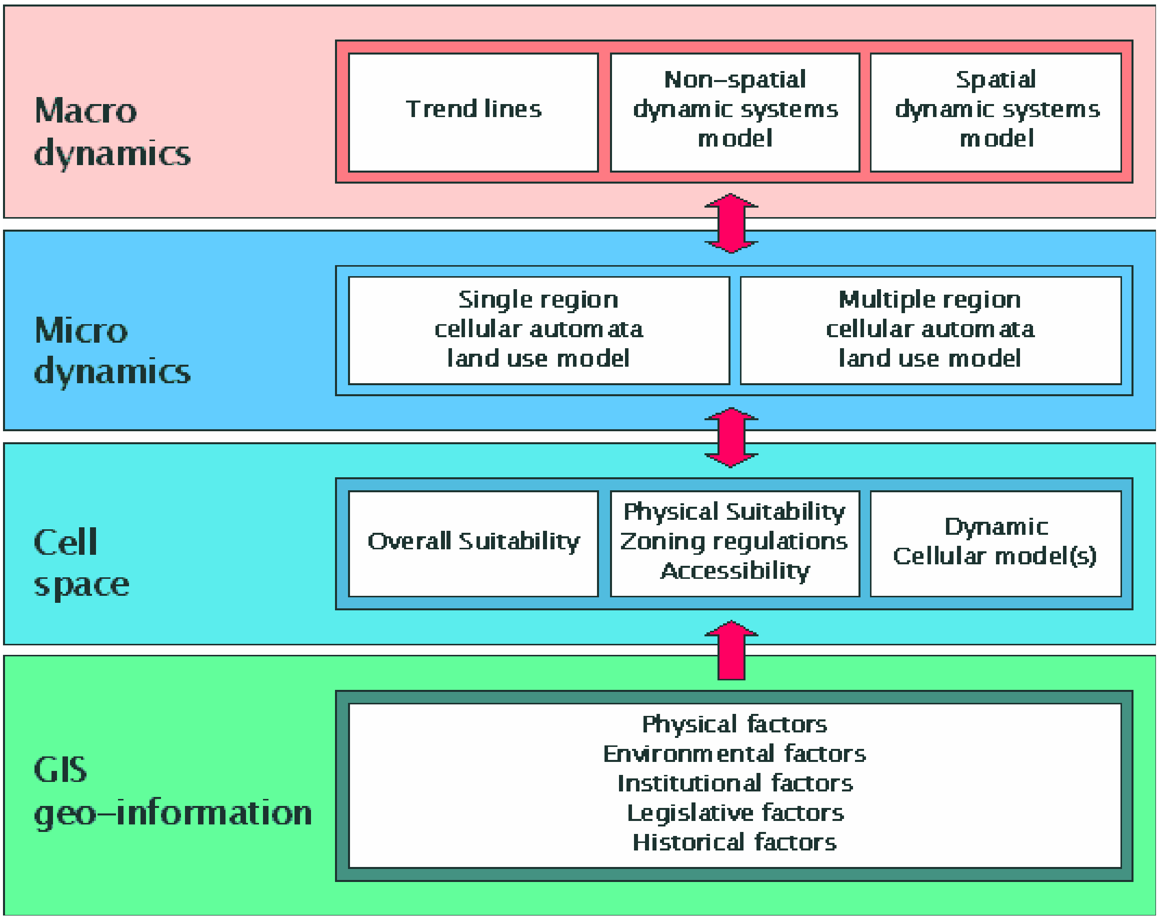

Figure 3.1: *Scheme showing the role of cellular automata land-use models as core elements in linking socio-economic and environmental models operating at different geographical scales.*

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 factors 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 based on the 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’ as clients need to be able to come and buy the goods and services quickly and easily. However, most natural land cover categories are best located in areas with poor accessibility. Otherwise they run the risk of being fragmented by the transportation networks or activities attracted by good access. 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.

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 CA itself unfold.

In most recent applications (Engelen et al., 1999), in principle any factor available from a GIS or a variable from another kind of (linked) cellular model can be incorporated into the CA 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.

The MOLAND model is equipped with this feature, hence enable to specify the cellular algorithm used in the model.

Both the coupling to macro models and to other kinds of cellular models, demonstrates how CA 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 (see Hahn and Engelen, 2000).

The calibration of the CA-model involves finding the appropriate values for the weighting parameter. This parameter has no absolute meaning; rather it is a relative value that is only meaningful within and among the different land-uses modelled. The general form of the distance functions is known from the literature and will serve as an overall constraint in the calibration process. Examples are: commercial activities generally withstand more spatial competition pressure than extensive agriculture, and, economies of scale will cause commercial activities to cluster. Within these overall constraints, the parameter can be partly estimated from frequency analysis carried out in the cell neighbourhood. However, such statistical approach is short in estimating the true process, the competition for space, which leads to the distribution of land-uses within the neighbourhood of each cell. Hence, further to the descriptive analysis of the neighbourhood, the model, with the best set of values for the weighting parameter is run from an initial known state till a final known state and the goodness of fit of the land-use map generated is evaluated.

4. THE INTEGRATED LAND USE MODEL OF REGIONAL GROWTH: GENERAL DESCRIPTION

Contrary to the MURBANDY model (i.e. first version of MOLAND model), which is essentially intended for the analysis of urban dynamics in metropolitan areas in the strict sense i.e. the actual area taken in by the metropolis and the area immediately surrounding it where urban expansion is very likely to take place in the near future, the MOLAND model is intended for larger urbanised regions. These include in addition to the metropolitan area also the larger hinterland of the city and, possibly the other cities, bigger and smaller. Thus, the development of the metropolis in relation to the larger region of which it is a part can be studied.

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 hierarchical geographical levels: the *Global* (the whole area covering administrative areas e.g. counties), the *Regional* (the individual counties) and the *Local level* (a number of cellular units 1 ha each) (see Figure 4.1, application of the MOLAND model to the Greater Dublin Area and its 9 counties). In the terminology used in this report, the combined Global and Regional levels constitute the so called macro-level of the model, while the Local level represents the so-called micro-level of the model.

Global level:
The 9 counties modelled as 1 region

Regional level:
9 Counties

Local level:
362000 1 to 4 ha-cells

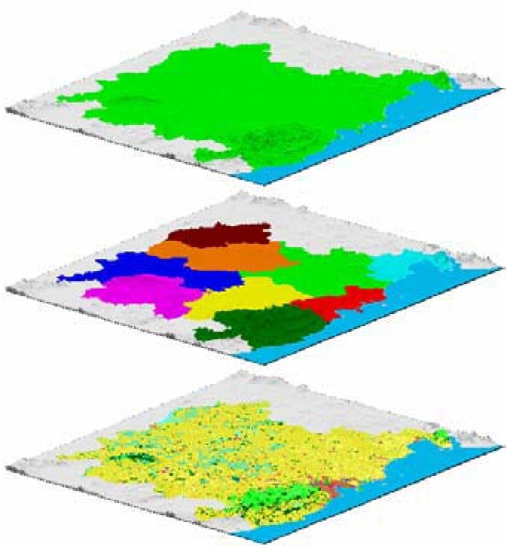

Figure 4.1. *The MOLAND model represents processes at three spatial levels: Global, Regional and Local. Greater Dublin Area example.*

The macro-model consists of 4 strongly linked sub-models (see Figure 4.2) representing the *Economic*, *Demographic*, *Land use* and *Transportation* sub-systems. The economic sectors are aggregated into four main categories: *Industry*, *Services*, *Commerce*, and *Port activities*. The population is assigned to four residential categories: *Residential continuous dense*, *Residential continuous medium, Residential discontinuous urban*, *Residential discontinuous sparse*.

The coupling between the three geographical levels has been decisive in the choice of the sectors at the Global and the Regional levels as well as the land uses at the Local level. This choice is further based on the distinct spatial requirements and specific spatial behaviour, as well as the quality, match, and availability of data at the three geographical levels of the model.

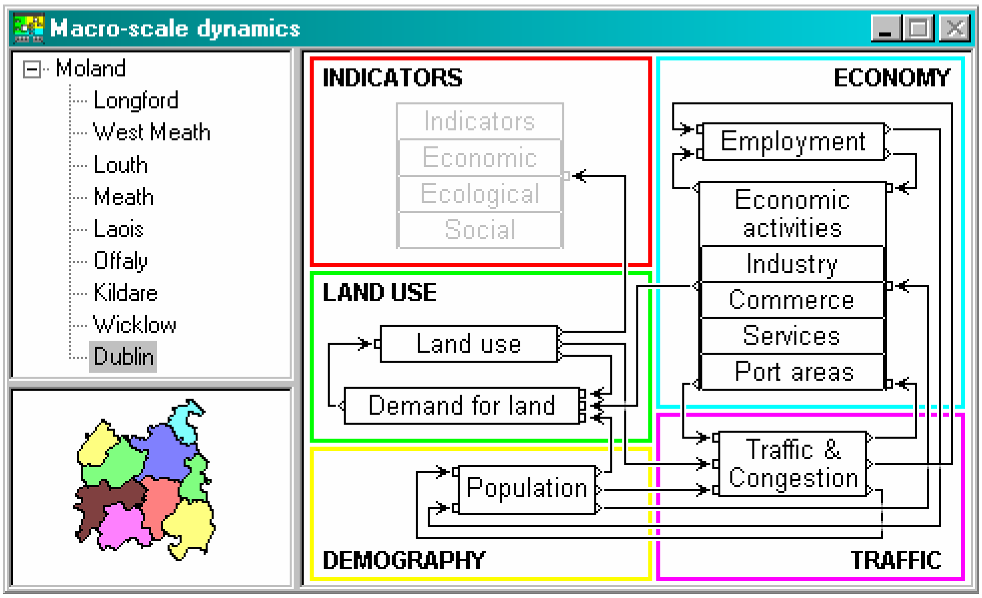

Figure 4.2. *The MOLAND macro-model consists of 4 sub-systems: Economy, Demography, Land use and Transportation.*

At the ***Global level***, the model integrates global figures taken from economic and demographic growth scenarios considering developments in the study area in the Irish context and the world beyond. From these, growth figures for the population and the jobs per economic sector are derived and entered into the model as trend lines. They are an input for the models at the Regional level.

Next, at the ***Regional level*** consisting of the 9 counties of the region, a dynamic spatial interaction based model (see for example: Wilson, 1974; White, 1977, 1978; Allen and Sanglier, 1979a, 1979b) arranges for the allocation of Global growth as well as for the interregional migration of activities and residents based on the relative attractiveness of the counties. The attractiveness of a county is determined by its importance as a centre of economic activity and housing, its position relative to the other counties, and its position in the public and the private transportation systems. Next to these, and novel in the context of interaction based models, detailed information relative to the changing quality of the space internal to the counties, obtained from the models at the Local level, is also considered. The mechanism driving the interregional exchanges of people and activities is based on the *relative potential calculation*.

Four sub-models can be distinguished:

• A *Regional economic module* (1) calculates the employment for each economic activity, its location and relocation among the regions.

• A *Regional demographic module* (2) deals with the demand for housing, its location and relocation among the regions.

• A *transportation module* (3) calculates the migration of people and businesses between the different regions. The position of the regions relative to one another and the quality of the roads connecting them play an important role in this.

• A *land-claim module* (4) translates the Regional growth numbers into spatial claims. The latter are passed on to the model at the Local (cellular) level for a detailed allocation.

Two principles are applied at this level: (1) claim for land is fixed and passed on as a hard constraint. This principle reflects the fact that for particular activities policies determine the amount and location of land that is to be created or to be preserved in a region. In MOLAND model it applies for *Port activities*, but in future versions of the model it could also apply for land uses such as: natural land, recreational land, and some of the agricultural activities. Or, (2) the principle of supply and demand is applied to regulate the densification of land use as well as its spatial allocation. This principle applies in particular to housing and the economic activities: *Industry*, *Commerce*, and *Services*.

At the ***Local level*** the detailed allocation of economic activities and people is modelled by means of a CA-based land use model (see for example: Couclelis, 1985; White and Engelen, 1993, 1997; Batty and Xie, 1994;). To that effect, the area modelled is represented as a mosaic of 362000 grid cells of 1 or 4 ha each (200 m on the side). Together they constitute the land use pattern of the area. Land use is classified in 24 categories, 8 of which are land use functions, 7 are vacant land uses, and 9 are land use features. This model is driven by the demands for land per region generated at the Regional level. In fact there are 9 identical cellular models running in parallel: one for each region. Four elements determine whether a piece of land (each 4 ha cell) is taken in by a particular land use function or not:

(1) The physical *suitability*. Suitability is represented in the model by one map per land use function modelled. It is a composite measure, on the basis of some 5 factor maps determining the physical, ecological and environmental appropriateness of cells to support a land use function and the associated economic or residential activity;

(2) The *zoning* or institutional suitability. Zoning too is characterized by one map per land use function. It is a composite measure based on master plans and planning documents available from the regional and national planning authorities and containing among others ecologically valuable and protected areas, protected culturescapes, buffer areas, etc. For three planning periods, to be determined by the user (for example: 1990-2000, 2000-2010, and 2010-2020), they specify which cells can and can not be taken in by the land use;

(3) The *accessibility*. The accessibility for each land use function is calculated in the model relative to the transportation system consisting of the public transportation system: light rail network, the railways and railway stations, and the private road network system consisting of the motorways, national, regional and local roads. 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, the quality of that link, and the needs for transportation of the particular activity or land use function;

(4) *Dynamics at the Local level.* While the above three elements are introduced into 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 immediate surroundings of a location. This is no longer the domain of abstract planning either, but 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, the model assesses the quality of its neighbourhood: a circular area with a radius of 8 cells, which is 1.6 km, 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 the 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 revival of decayed neighbourhoods initiated by the arrival of 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 the 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 Regional demands are satisfied, cells will change to the land use function for which they have the highest potential. Consequently, the transition potentials reflect the pressures exerted on the land and thus constitute important information to those responsible for the design of sound spatial planning policies.

The linkage between the models at the Global, Regional and Local levels is bi-directional and very intense: the Global growth figures are imposed as constraints on the Regional models, the Regional models distribute and allocate the Global growth to the 9 counties and impose on the cellular models the Regional growth numbers. The cellular models finally determine at the highest level of detail where the growth is taking place. In this process, the cellular models return to the Regional models information on the quality and the availability of space for further expansion of each type of economic or residential activity. This information is an input into the spatial interaction calculations at the Regional level and it will influence strongly the relative attractiveness of the individual regions. 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.

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