Research Institute for Knowledge Systems BV

Spatial simulations with Cellular Automata: recent advances in Geography

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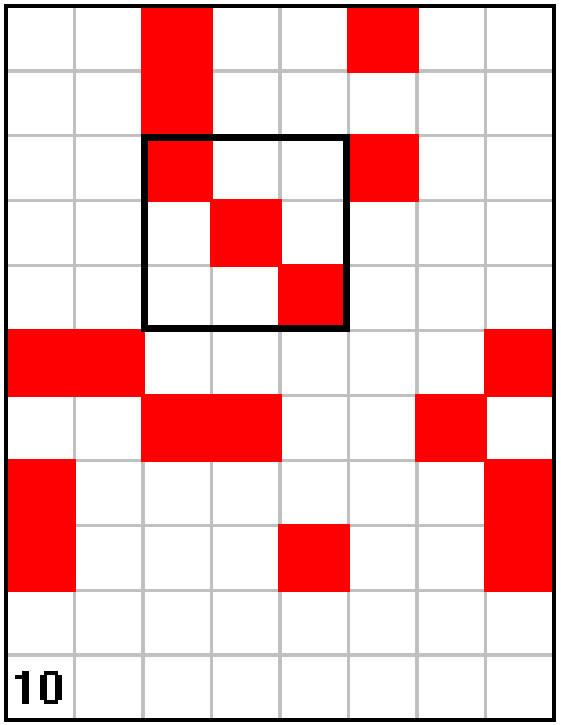
Contents of the presentation

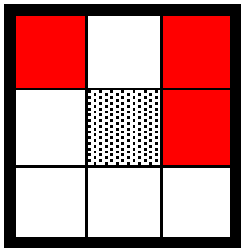
- A short introduction into Cellular Automata;
- Very brief historic overview of CA-modelling in Geography;
- 1 Example of a hybrid CA-model used for planning and policy making purposes: Environment Explorer model of the Netherlands (In Dutch: LeefOmgevingsVerkenner, LOV);
- Calibration and validation of the above model

Example of a Cellular Automata: Conway's Life *(Gardner, 1970)*

2-D ***cellular space***
consisting of identical cells



neighbourhood
(Moore)



cells are in 1 of 2 ***states:***

dead,

or alive

state changes due to ***transition rules:***

- live cell stays alive if 2 or 3 of its neighbours are alive, otherwise it dies.
- dead cell will come to life if it has 3 live neighbours.

Why are CA interesting for modelling Spatial Systems?

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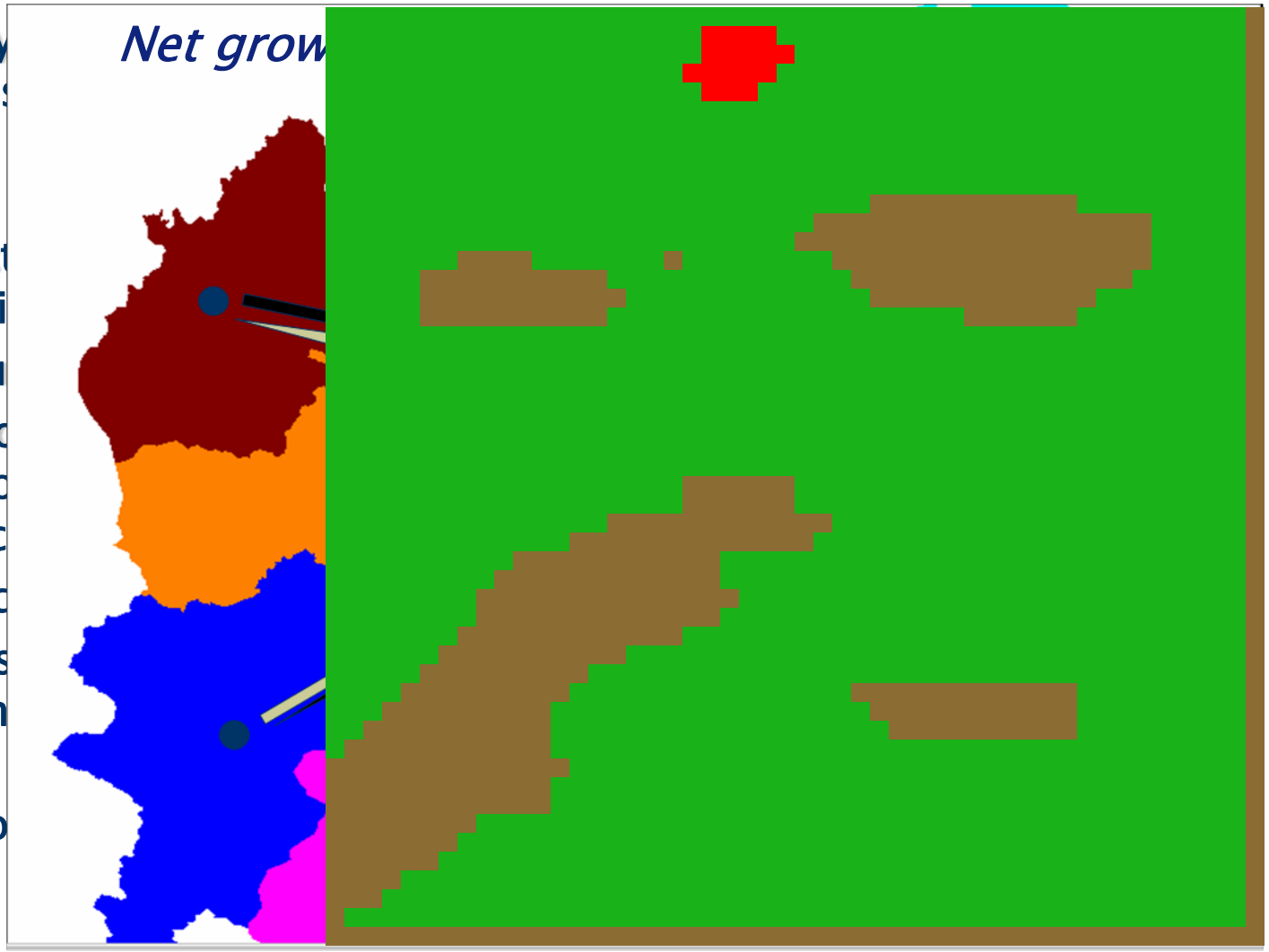


CA's in spatial sciences

- Concept introduced by Von Neumann, Ulam and Burks in late 1940-ies and 1950-ies;
  - Self-reproducible mechanical automata;
- Conway's 'Game of Life' (Gardner, 1970)
- Rapid development since Life:
  - In artificial intelligence: A-Life (Burks, Holland, Langton, …, Santa Fe)
  - In mathematics/physics: Digital Mechanics (Toffoli & Margolus, Fredkin: *'the universe is a cellular automata'*)
- Tobler (1979) defines CA as 'geographical models', but also 'too simple to be usefully applied' (Life)
- From the mid 1980-ies some theoretical work on CA;
- Since mid 1990-ies exponential growth of applications aimed at:
  - Improved understanding of spatial dynamics;
  - Adding geographical realism to CA's and linking CA's with traditional geographical, sociological, ecological and economic theory;
  - Linking GIS and CA;
  - Building useful and practical applications;
  - Methods for Validation, Calibration, Uncertainty, Error propagation,…

Environment Explorer
Aims and Ambitions

- Spatial Decision Support System for the Integrated Exploration and Assessment of Socio-economic and Environmental Policies in the Netherlands:
  - **Integrated Land use model**: Economy, Demography, Environment, Transportation as elements determining Land use change (= high resolution land-use transportation model of the Netherlands);
  - To explore the changing **(Life-)Environment** of the Dutch in **Economic**, **Social** and **Ecological** terms (planning concept since 1996, 5th Plan);
  - Developed to evaluate mid to long term policies (horizon 2030):
    - **Autonomous developments** (dynamics) of the system;
    - Ex-post evaluation of **past policies**;
    - Ex-ante evaluation of **actual policies**;
    - Ex-ante evaluation of **alternative** and **potential future policies**;
  - Explorative, fast response time, easy to use, flexible, usable in participative decision making sessions.

Origine of the product

Product developed since 1997 for:

- Ministry of Housing, Spatial Planning and the Environment:
  - RIVM, National Institute for Public Health and the Environment;
  - RPD, National Planning Board.
- Ministry of Transport, Public works and Water Management:
  - RIKZ, National Institute for Marine and Coastal Management;
  - RIZA, National Institute for Inland Water Management and Waste Water Treatment;
  - AVV, Transport Research Centre.
- Inter Provincial Coordination Committee
  - Provinces of Utrecht, North Holland, Limburg, Gelderland, …

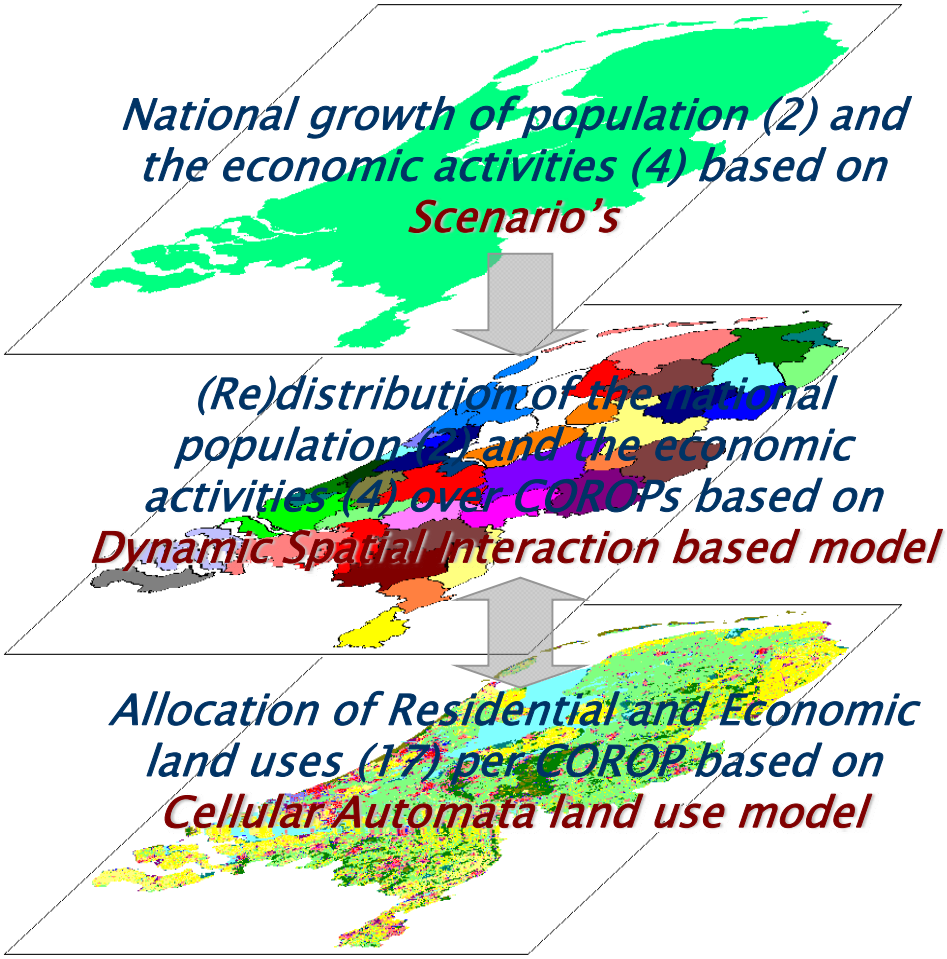
Environment Explorer

Models at 3 coupled spatial scales

National,
Netherlands in EU

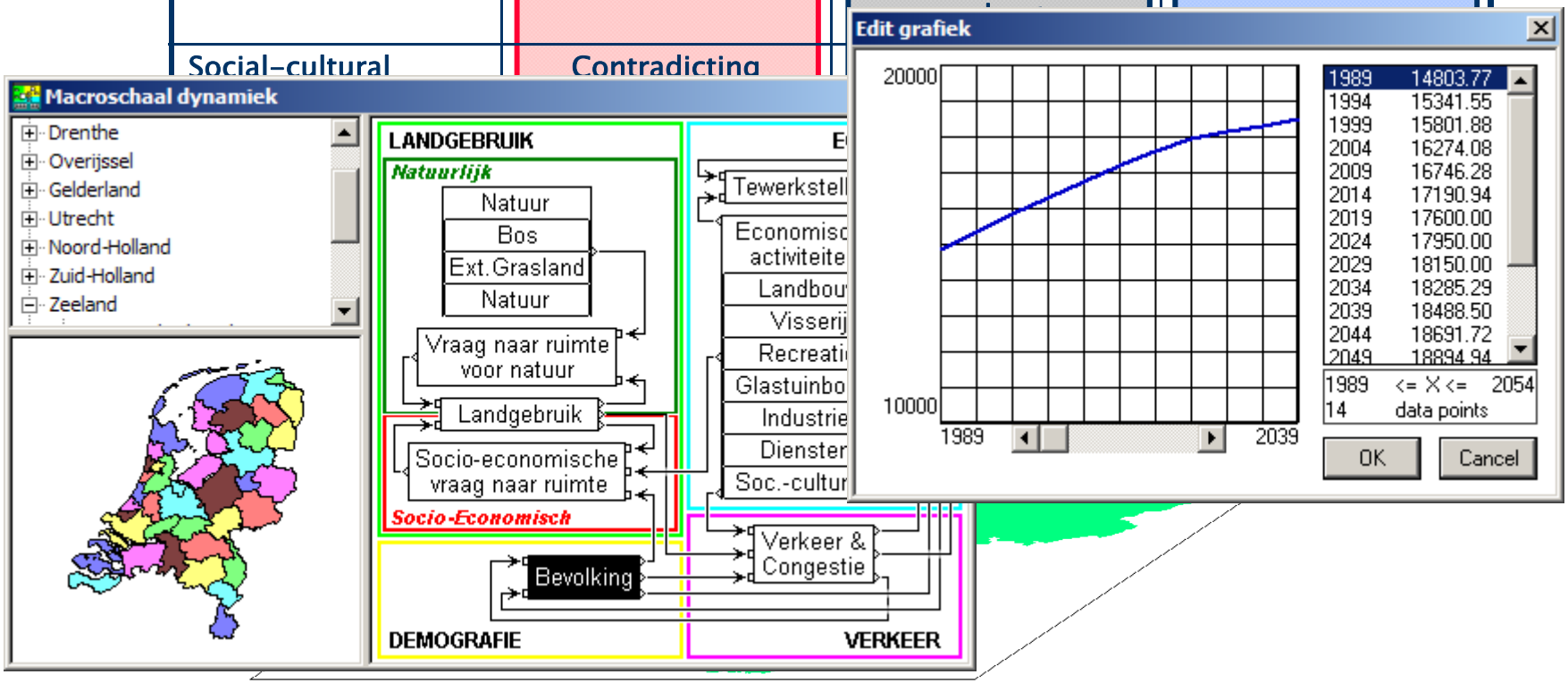
Regional,
40 COROP regions

Local,
351000 cells 25ha

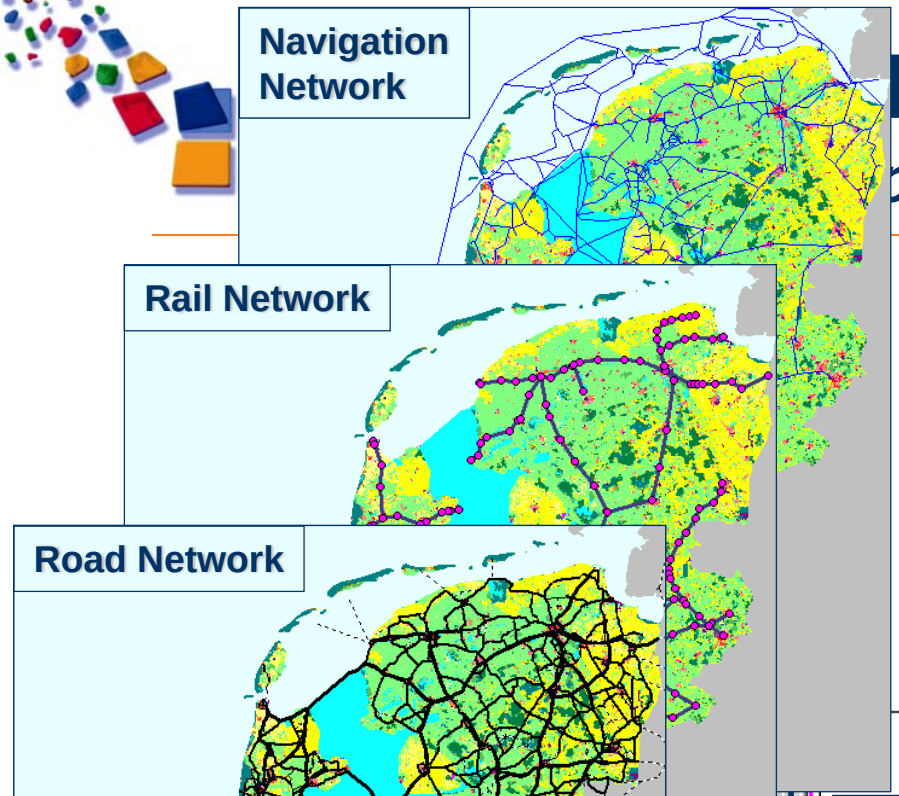


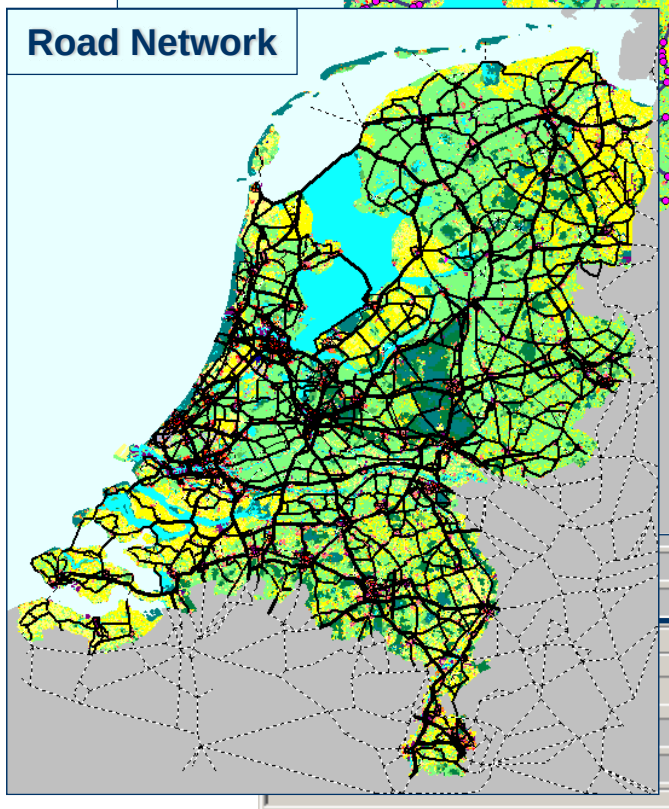
National:
Scenario's (LTE, Plan bureau, …)

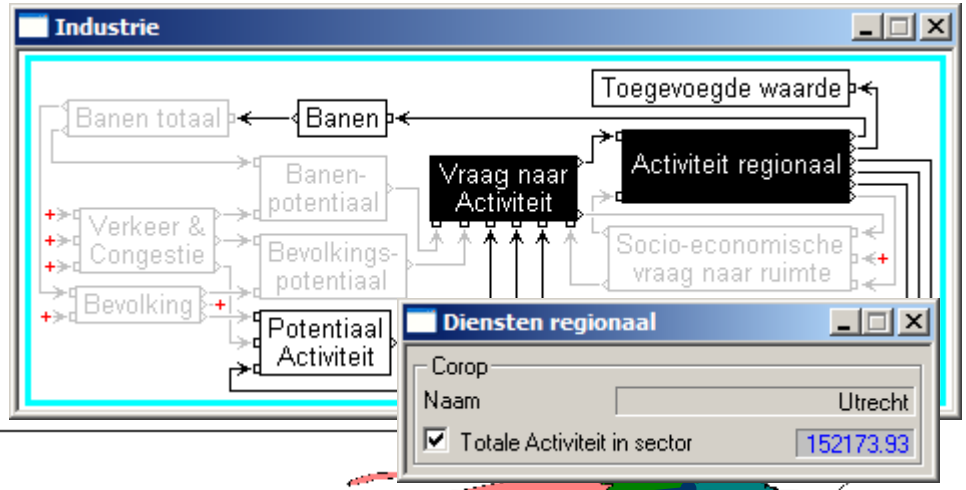
	Divided Europe	Global Competition	European Coordination
International	Stagnating European Integration	Europe à la carte	Europe of two speeds
Demography	Immigration low	Immigration	Immigration high
Social-cultural	Contradicting		



Regional:
patial interaction based







$$\frac{\Delta X_{i,r}}{\Delta t} = f\left(X_t, N_t, d_i\right.$$

$$f\left(\right.$$

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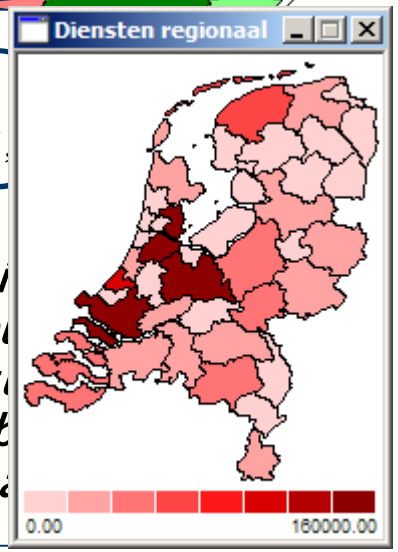
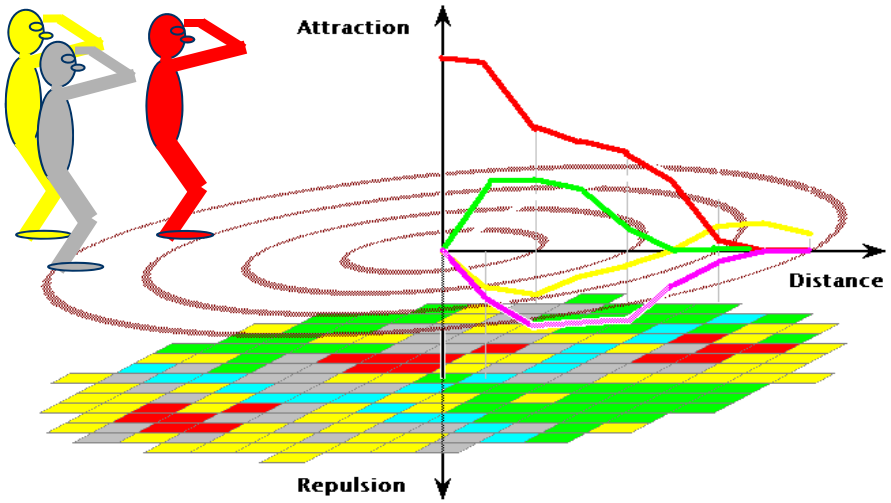
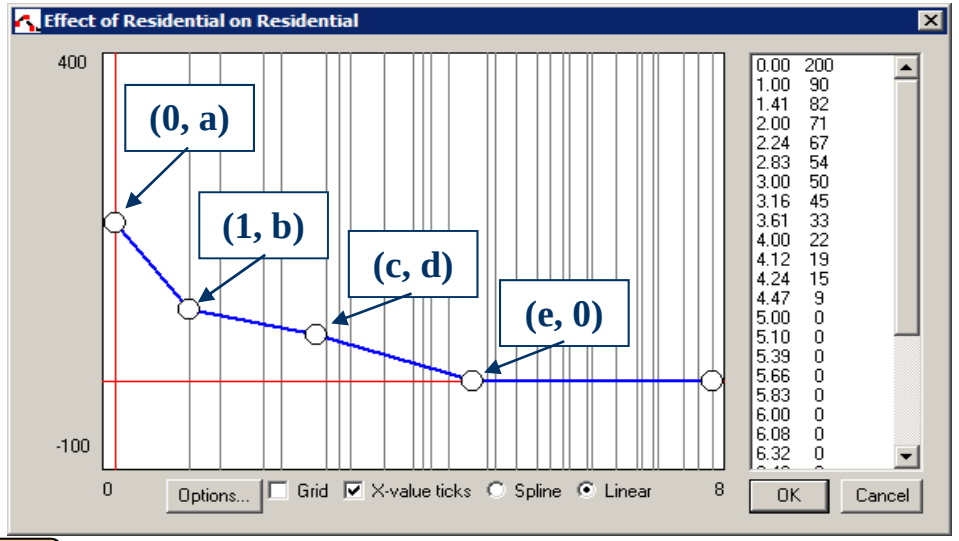
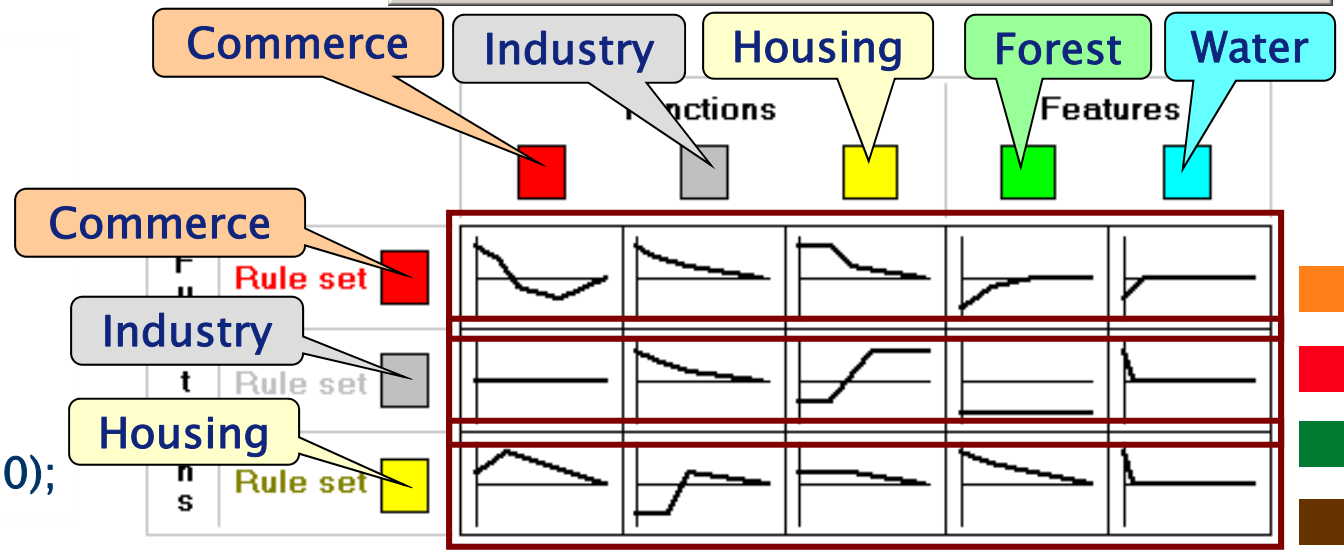


Local:
RIKS' Constrained Cellular Automata (1992)



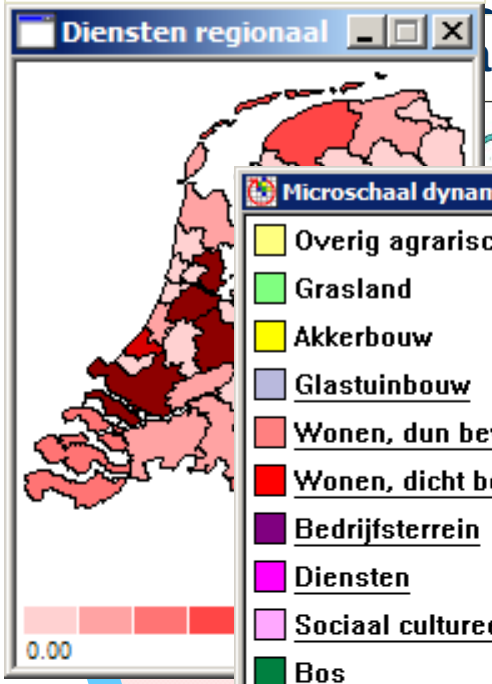


- Neighbourhood with radius of max. 8 cells, 196 cells
- 17 land uses:
  - 10 Active functions;
  - 3 Passive functions;
  - 4 Static features.
- 500 m resolution;
- 1 model per COROP (40);



Land use dynamics in a hete… geograp…c

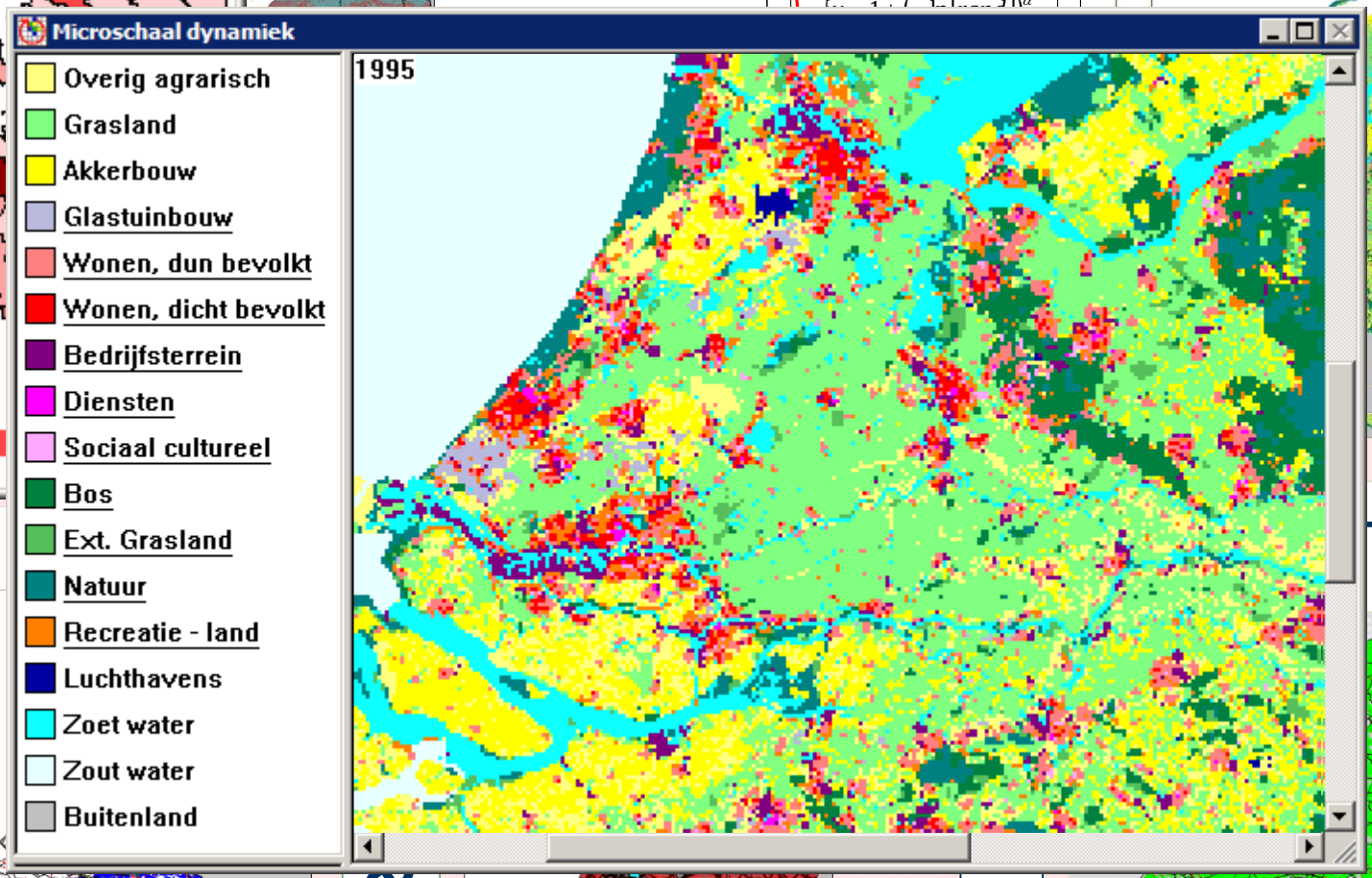
Regional demands



…bility

Stochastic perturbation

Land use at time T+1



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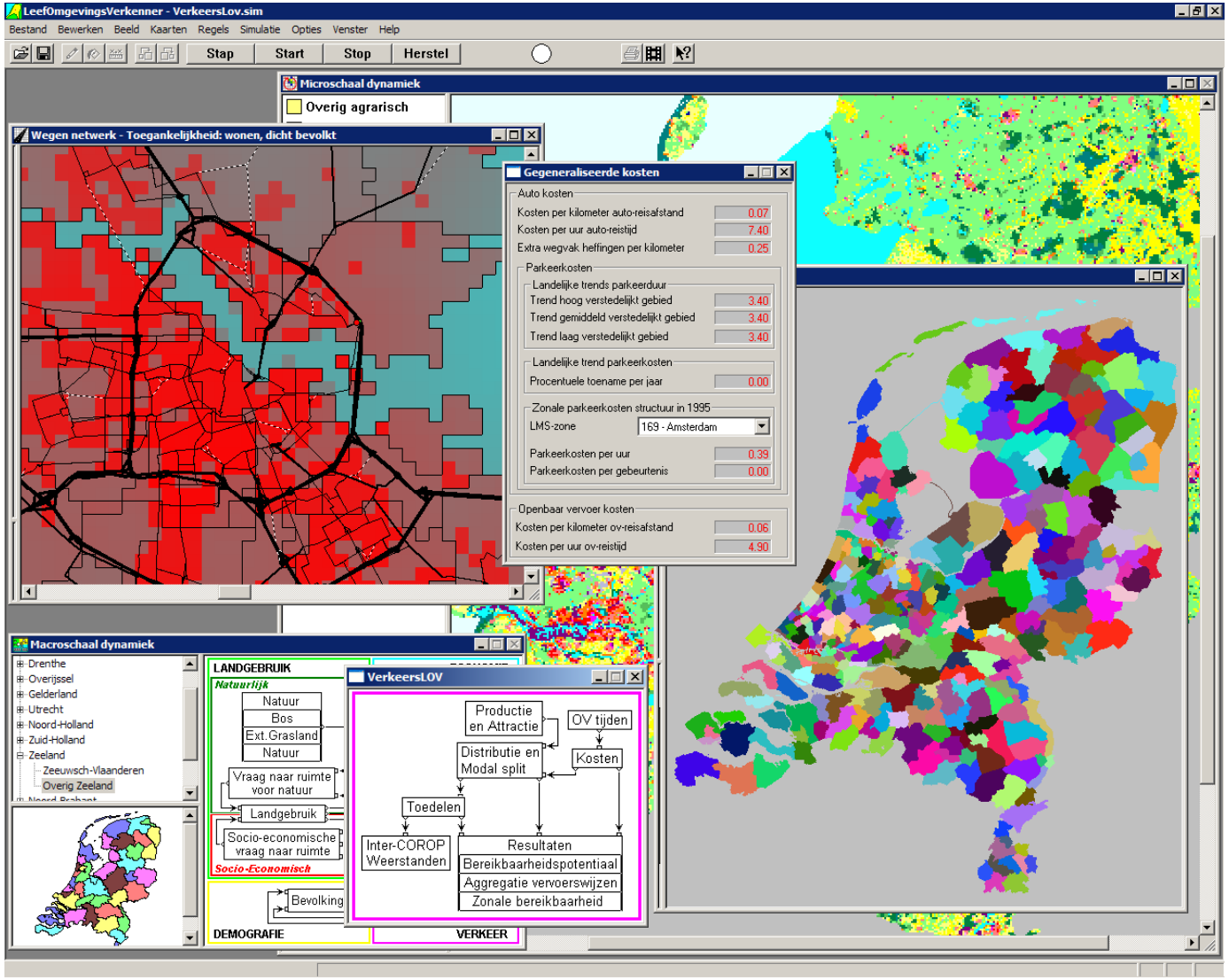
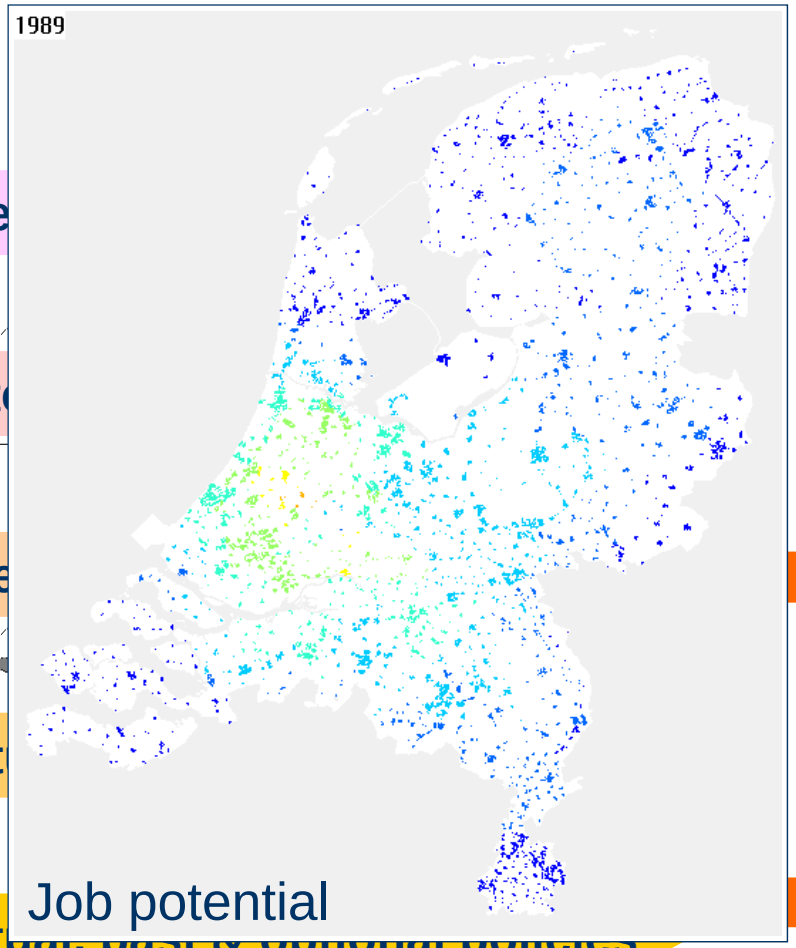
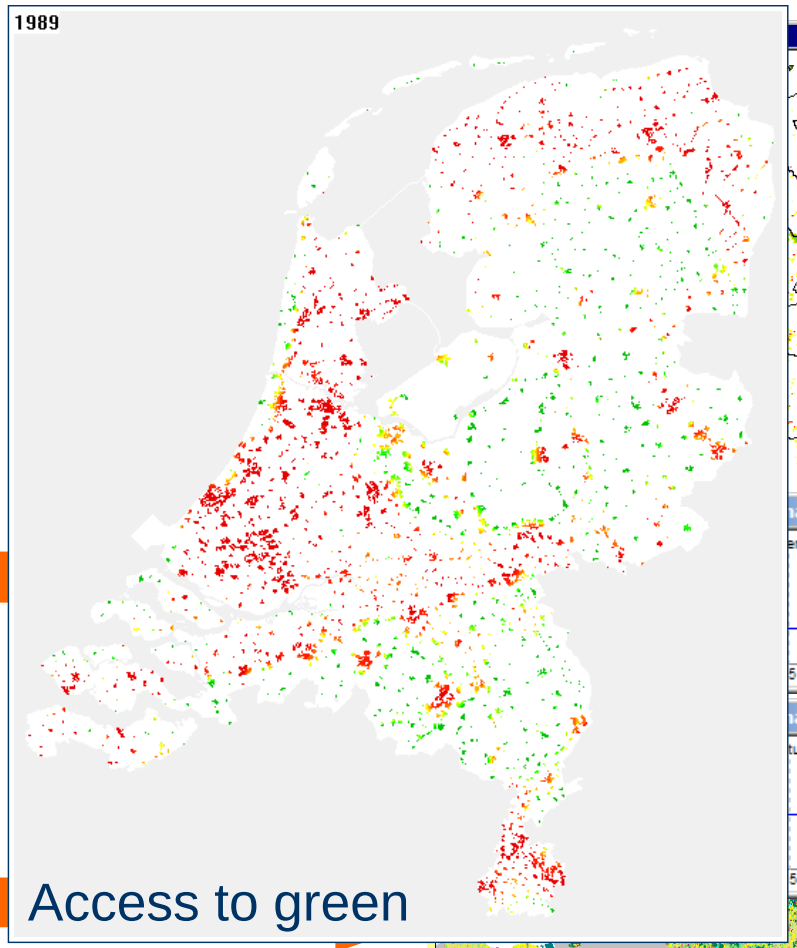
Environment Explorer:

dynamic, high-resolution land use-transportation model



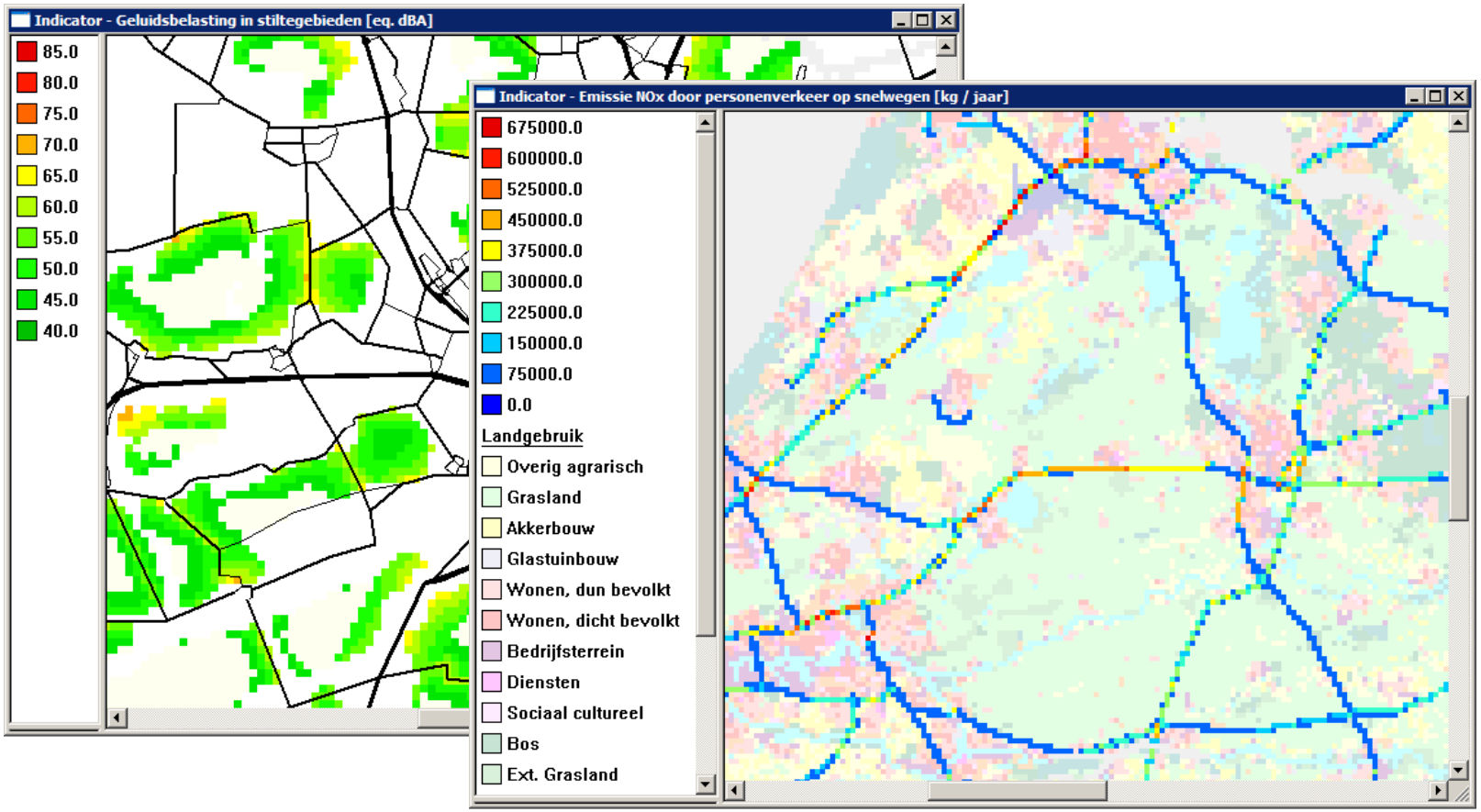
A tool for exploring Planning and Policy options





Effects of traffic on citizens and the environment

- Noice pollution (> 40dBA) in protected and silence zones;
- Air pollution (NOx) due to private vehicles on motorways.



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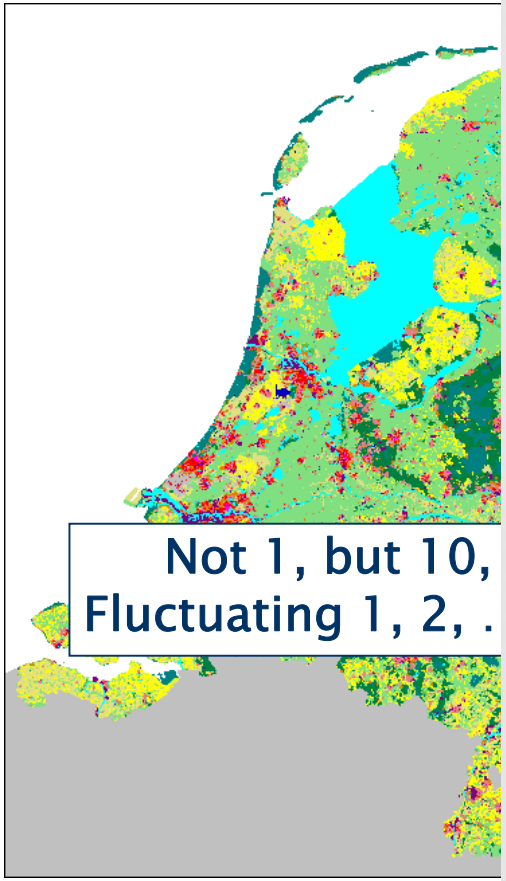
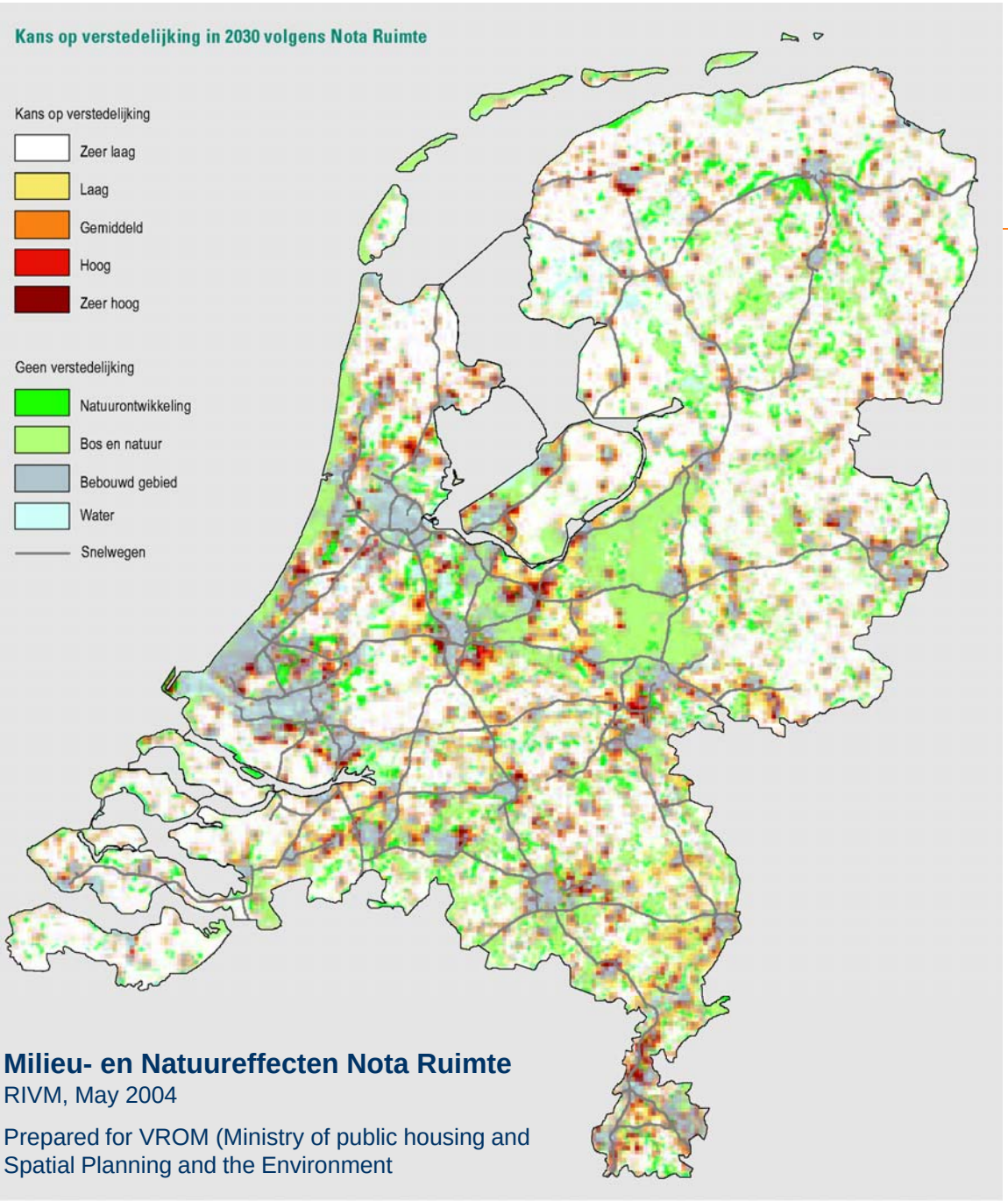


Not 1, but 10,
Fluctuating 1, 2, .



Milieu- en Natuureffecten Nota Ruimte
RIVM, May 2004

Prepared for VROM (Ministry of public housing and Spatial Planning and the Environment

Figuur 2.3: Modelmatige ruimtelijke projectie 2030 van de Nota Ruimte

Calibration and Validation (2003)

- Major (re-)calibration effort
- … aimed at the development tools to support (semi-) automatic calibration:
  - Emphasis of policy exercises change, hence the model, the set of variables and the land uses modelled change;
  - Data are updated regularly;
  - Models improve over time.
- Calibration period: 1989-1996;
- Validation period(s): 1996-2000; 1989-2030;

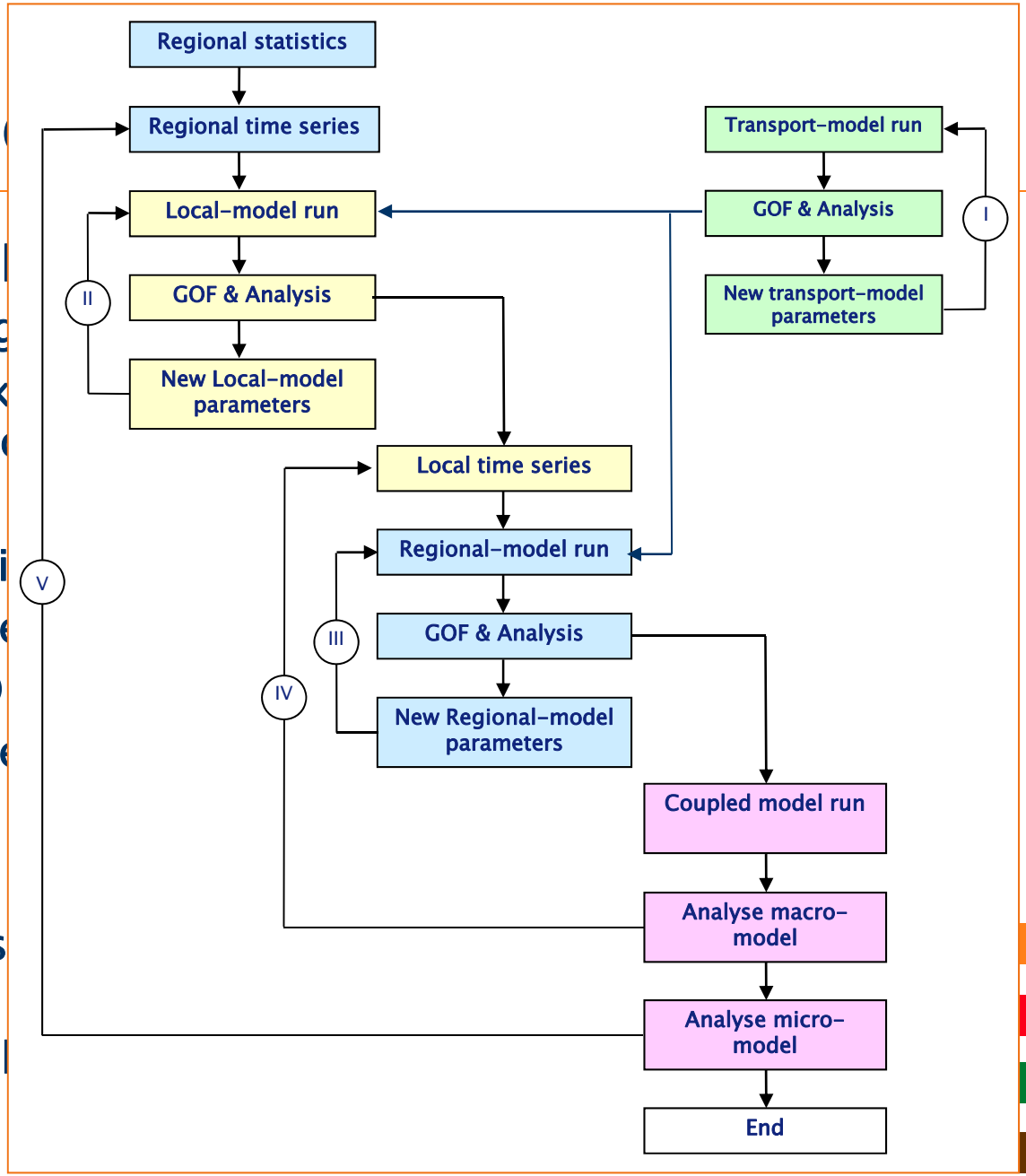
Stepwis

Modular model ➔ enal

- One main disadvantag
  - Essential feedback
    some duplication
- Many advantages:
  - Model specific cali
  - Emphasis on mode
  - Model specific GO
  - Reduction of proce

Iterative process

- First decoupled: use s
  output
- First Local (cellular), t



Objective function Regional model

(Van Loon, 2004)

Measured values

Simulated values

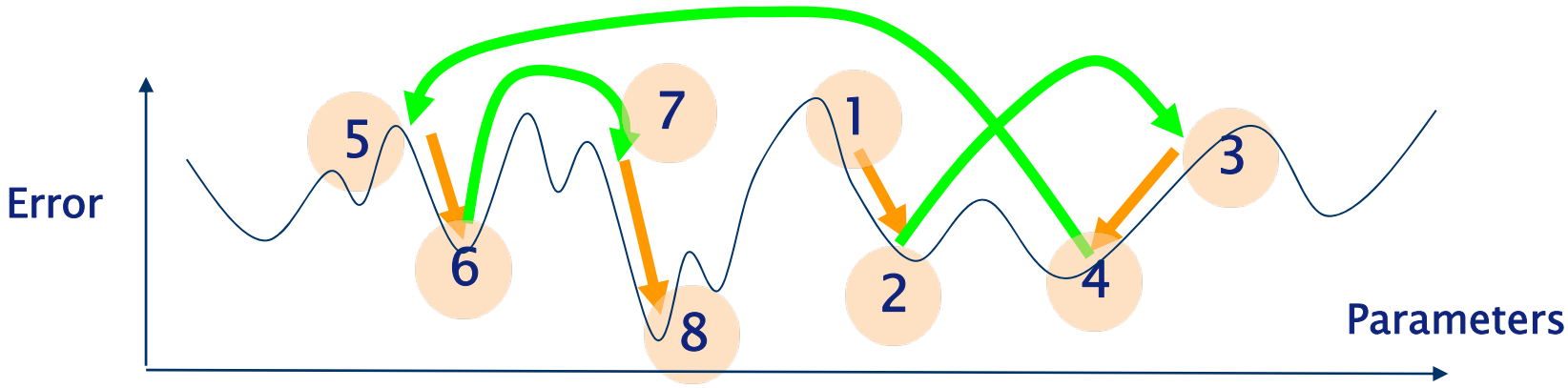
$$\text{Minimize} \sum_{K=1}^{NrSectors} \sum_{i=1}^{Nr\ Regions} \left(w_K \cdot \left(w_\beta \cdot \left(\frac{Xref_{Ki} - X_{Ki}}{Xinit_{Ki}} \right)^2 + w_\delta \left(\frac{Wref_{Ki} - W_{Ki}}{Winit_{Ki}} \right)^2 \right) \right)$$

Initial values

- Minimize error
- Emphasis on sector(s)
- Emphasis on two parameter sets:
  - 'Attractiveness parameter set'
    - Parameters influences the attractiveness and hence activity levels (jobs and residents)
  - 'Density parameter set'
    - Parameters influence the density and hence number of cells

Calibration algorithm Regional Model

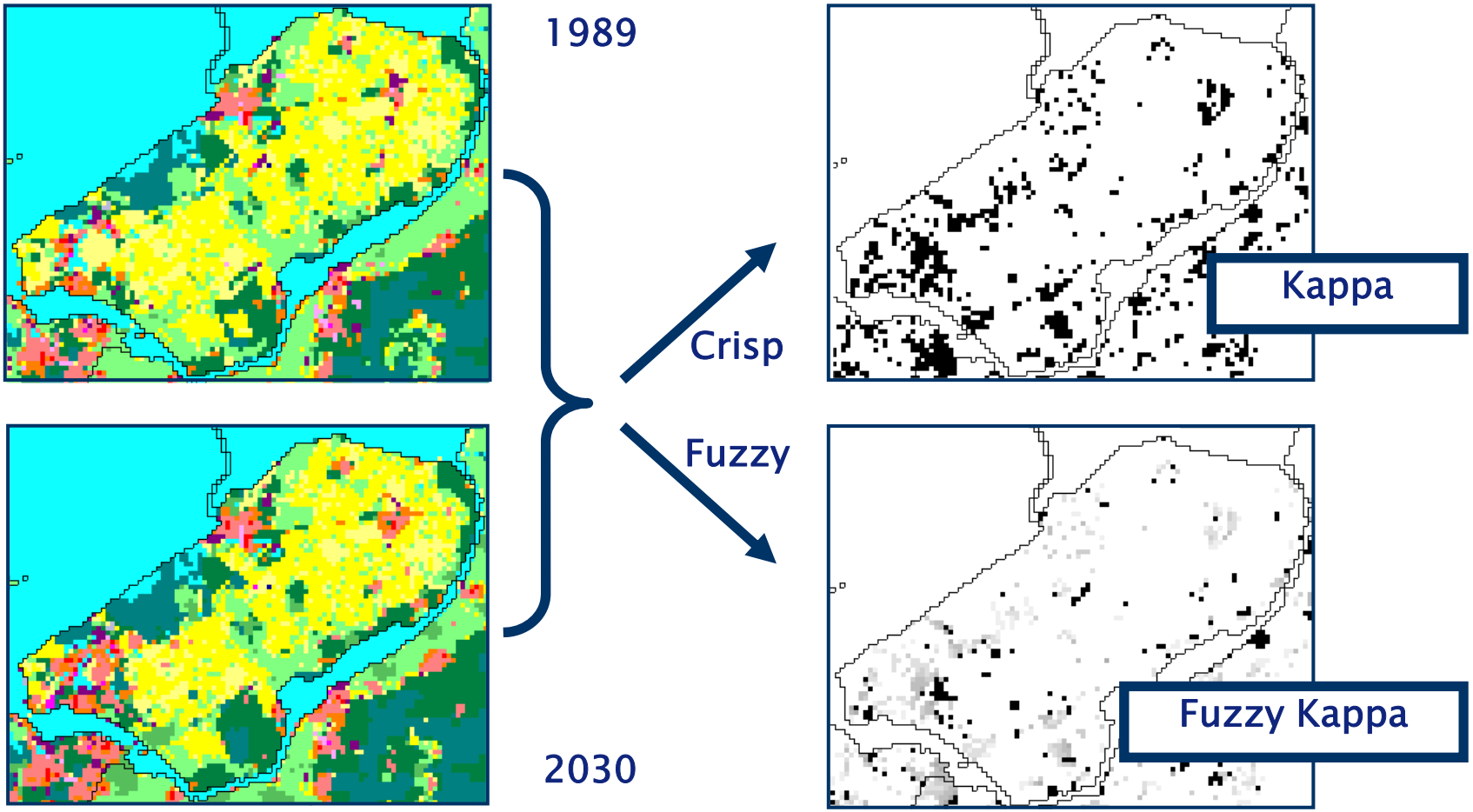
- Many parameters and local optima … but, relatively short processing time;
- Combined optimisation algorithms:
  - Hill climbing / Golden section search:
    → Convergence towards a local optimum;
  - Random search (≈ mutation step in GA's):
    → Search for a global optimum;
  - Simulated annealing;
  - Combine their strengths and get rid of their weaknesses.



Goal function Local model

Fuzzy Kappa, Alex Hagen, IJGIS, 2003

Fuzzy map comparison: 'Maximize similarity at higher level of abstraction'



Calibration algorithm Local model

(Improved Straatman et al., CEUS, 2004)

- Iterative optimization of CA-distance rules:
  - Improves an initial rule-set;
  - Semi-automatic: includes expert evaluation of the resulting rules to remove rules 'not to be explained by theory';
  - 'Processing time' versus 'Time for analysis'.
- Carry out selecti
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  - Which can be s
  - Which adjustm
- Adjusting the rul
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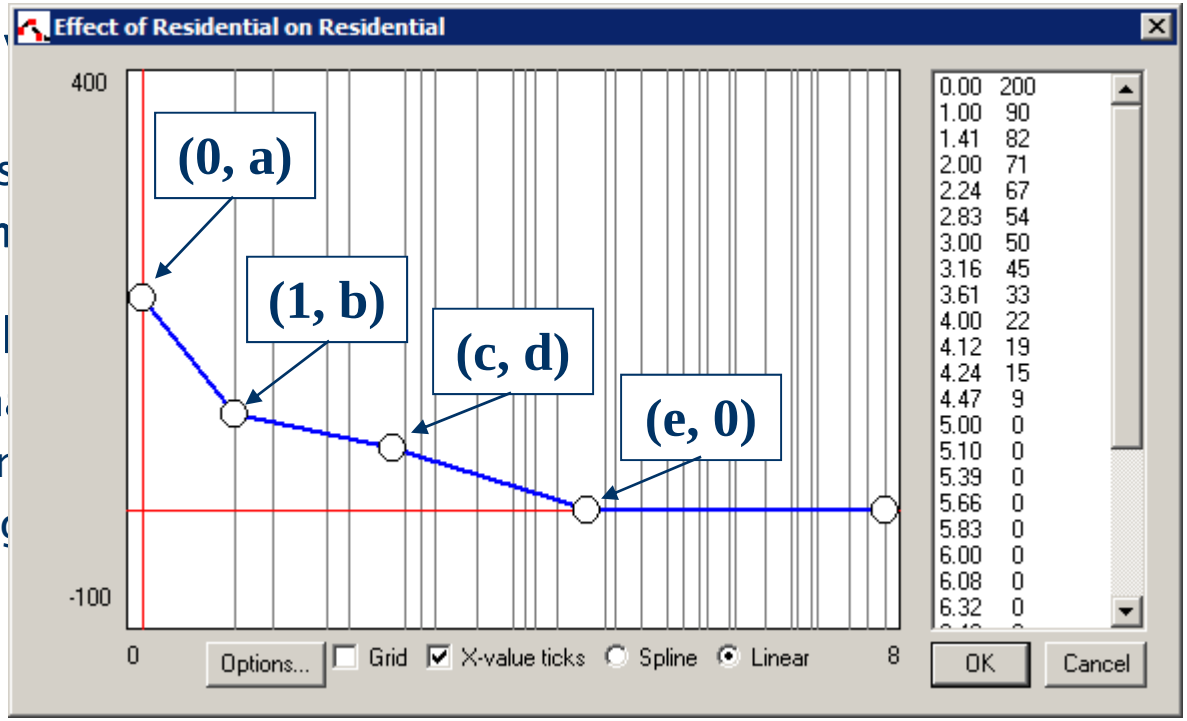


Results

Calibration period

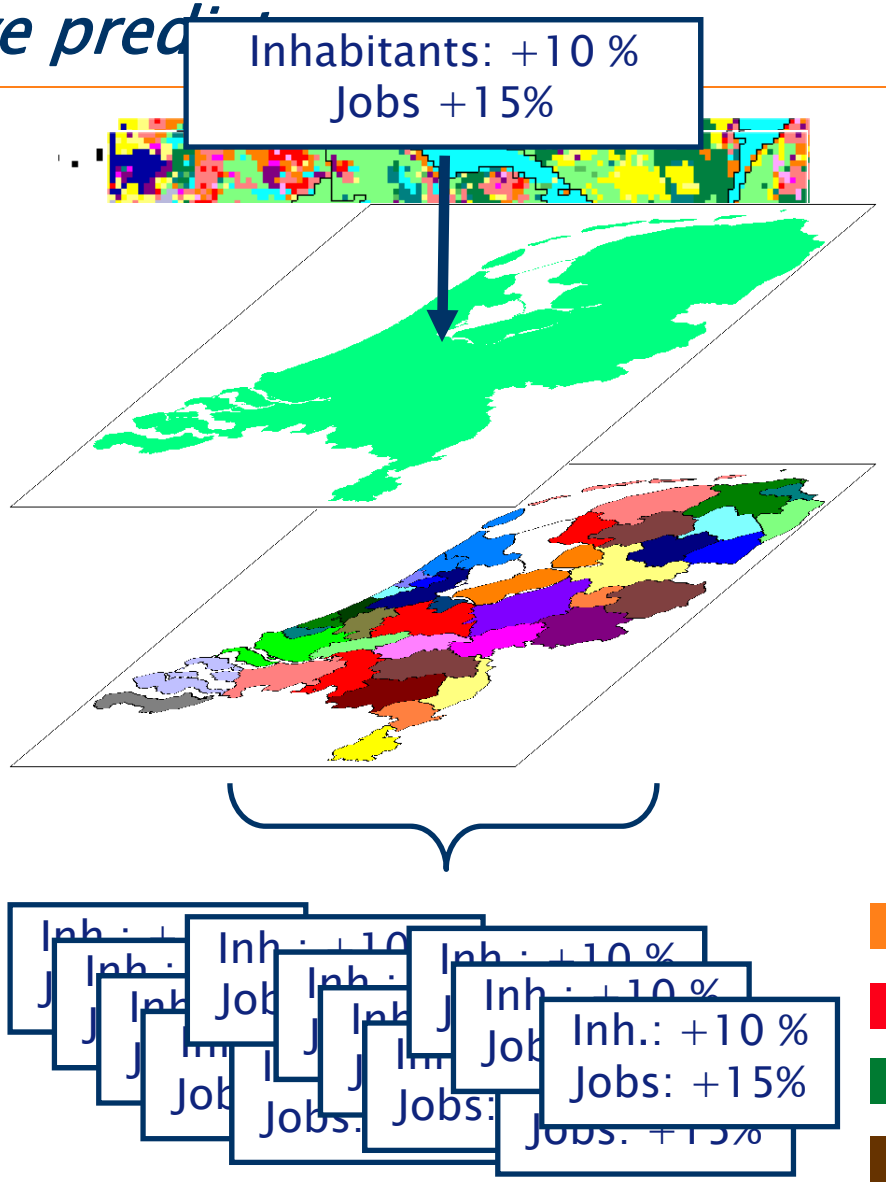
	Local scale Fuzzy Kappa [-]		Regional scale Activity [% growth]		Regional scale Area [cells]	
	EE		EE		EE	
1989-1996	0.94		3.9		3.3	
1996-2000	0.91		5.2		7.7	

Validation period

Interpretation of Results:

Naive predi

- Minimizing the goal functions, yes, but how good are the results in absolute terms?
- Interpretation of the level of error
  - Comparison with a minimalist model (null-model, a naive predictor)
  - Situation today is the best prediction for tomorrow
- Local: Random Constraint Match
  - Map changes minimally due to the number of required and known changes
  - Changes are distributed randomly
- Regional: Constant Share model
  - Proportional distribution of activities over all regions remains constant



Results

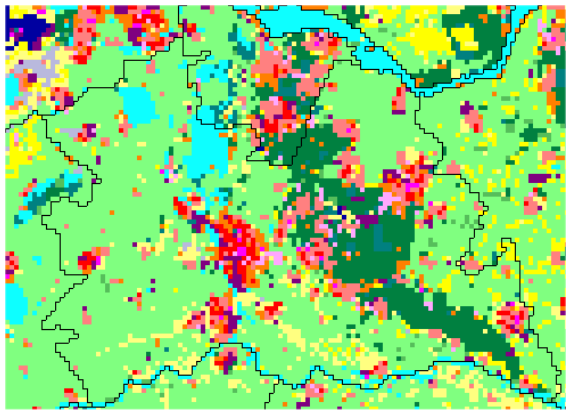
- Compare EE results and naive predictors with observed data
  - Micro model: Random Constraint Match (RCM) [Fuzzy Kappa match]
  - Macro model: Constant Share model (CS) [% growth not captured}

	Local scale Fuzzy Kappa [-]			Regional scale Activity [% growth]			Regional scale Area [cells]		
	EE		+/-	EE		+/-	EE		+/-
1989-1996	0.94		+	3.9		+	3.3		+
1996-2000	0.91		-	5.2		-	7.7		-

- Good calibration 1989-1996
- Mediocre validation 1996-2000

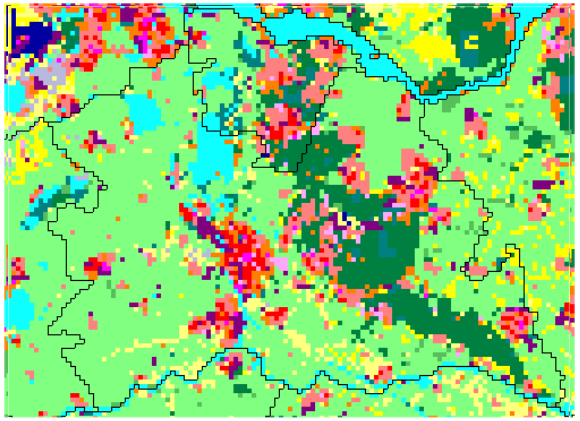
Influence of the length of the validation period

For the short time horizon, naive predictors are better models, but, what about the long term ?



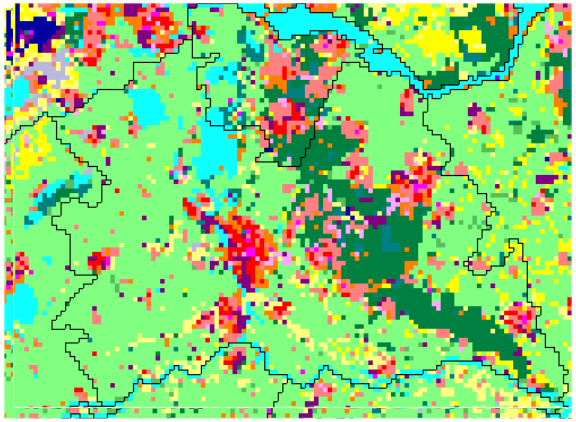
1989

DATA



2090

RCM



Influence of quality of the data

- Base maps 1989, 1993, 1996 and 2000
- Dominant land use at 500 m resolution
- “Dubious land use changes”

1996	Ag
	Gre
	Urb
	Nat
	Rec
	Fea

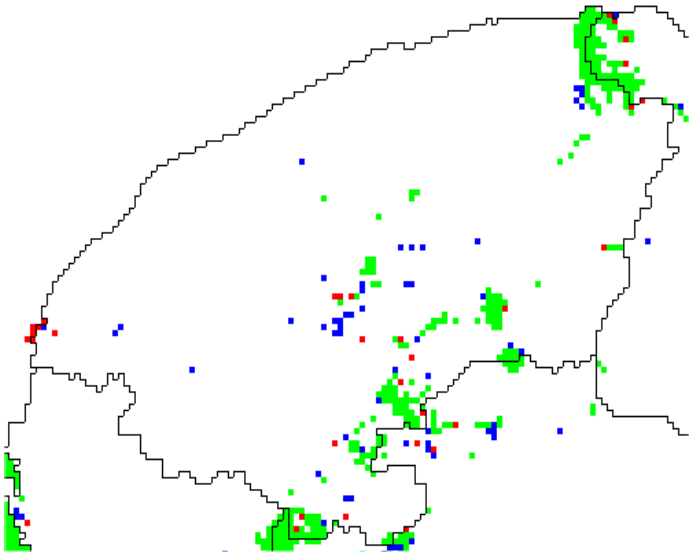
Surface waters in North-Friesland

Not in 1989 nor in 2000

In 1989 and in 2000

Only in 1989, not in 2000

Only in 2000, not in 1989



Conclusions Calibration/Validation

- Calibration lead to a modification and simplification of the model!!
- Calibration methods work reasonably fine:
  - They produce much better results and faster than the expert;
  - but, do not guarantee an optimal solution (search space is too big);
  - and, do not take into consideration data quality sufficiently;
  - and, lack currently the intelligence to distinguish between the 'process' and 'pure hazard';
  - and, are likely to over-calibrate the model on just one possible path of the system (= the historic path);

Environment Explorer: Evaluation

- Successfully used for the integrated analysis of spatial planning policies at the National and the Provincial level in both workshops and individual sessions

- Is evaluated positively because of:
  - Added value as a tool for analysis, discussion and communication;
  - Provides better insight in the dynamics and the interrelated nature of functions, processes, cause and effect relations;
  - Provides insight in the effects of policies in the own discipline and that of others;
  - Enables the objective evaluation of the relative value of more alter-natives than would otherwise be considered in a policy exercise;

- Is evaluated less positively because of its complex nature.
  - It models a complex reality and requires a minimum of knowledge of the domains represented by those using it. For many actively involved in the planning field this is beyond their capacity.

Cellular Automata: State of the art

- New tools for spatial scientists:
  - Only recently 'discovered' in the spatial sciences (Tobler, 1970);
  - … but, the mathematical and computational framework has been extensively studied for the 'simplest' of CA models only;
  - … and, traditional Cellular Automata are 'too simple to be useful' (Tobler) to model socio-economic systems;
  - Hence, how much of the scientific integrity remains when the elements of the original framework are amended? (Couclelis, 1997);

- Field in full expansion:
  - Theoretical, but also dedicated empirical work is needed for the definition of more appropriate transition rules;
  - More appropriate methods and tools for calibration, validation and uncertainty management are wanted;
  - More conceptual work is needed on the intricate linkages between: spatial resolution, size of the neighbourhood, dynamics of the modelled system, number of iterations, number of states modelled.

The END

To find out more about Environment Explorer:

- http://www.riks.nl/projects/LOV
  - Reports, Brochures, Publications, ….
  - A copy of the Environment Explorer model (requires signing a licence agreement with the RIVM).