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?

- Base hypothesis: State changes in each cell are fully determined by the state of cells in a relatively small neighbourhood and the spatial interactions vis-à-vis these cells;
- Spatial interaction is limited compared to Dynamic Spatial Interaction based models (e.g. Transportation models). Exception: multilevel (meanfield) grid (Anderson et al., 2002);
- Computationally efficient. Allow for extreme spatial detail;
- Morphogenesis: Macroscopic, complex spatial structures are the result of very many local decisions and interactions at short distances only: paradigm of Self-organisation;
- Super class of Finite Elements Methods;
- Subclass of Agent Based Models (i.e. Individual Based Models): bottom-up approach to spatial modelling.
- Enable the straightforward integration of GIS layers and more traditional models.

Net growth = Gains - Losses
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 growth of population (2) and the economic activities (4) based on Scenario’s

(Re)distribution of the national population (2) and the economic activities (4) over COROPs based on Dynamic Spatial Interaction based model

Allocation of Residential and Economic land uses (17) per COROP based on Cellular Automata land use model
### National: Scenario’s (LTE, Plan bureau, …)

<table>
<thead>
<tr>
<th>International</th>
<th>Global Competition</th>
<th>European Coordination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divided Europe</td>
<td>Stagnating European Integration</td>
<td>Europe à la carte</td>
</tr>
<tr>
<td>Demography</td>
<td>Immigration low</td>
<td>Immigration high</td>
</tr>
<tr>
<td>Social-cultural</td>
<td>Contradicting</td>
<td></td>
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</tbody>
</table>

- **Théo Quant, Besançon**
Regional: Dynamic spatial interaction based

All economic activities, jobs, population, … zoning, suitability, accessibility, … in zone and at a distance
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 heterogeneous geographical space

Time Loop

Land use & Interaction weights & Suitability

Stochastic perturbation

0.51 \( \alpha \)

\[ Z_{\text{randvt}} = \ln(1 - \alpha) \]

Transition-potential = Transition Rule

Change cells to land-use for which they have the highest transition potential until Regional demands are met.

Land use at time \( T+1 \)

Regional demands
Environment Explorer: dynamic, high-resolution land use-transportation model
A tool for exploring Planning and Policy options

Scenarios
- Actual, past & optional policies
- External events
- Actual or future trends
- Alternative visions

Cellular
- Land use, Economic, Environmental and Social indicators

Regional
- Population, Jobs, Economic activity, Transportation indicators

Job potential
Access to green
Effects of traffic on citizens and the environment

- Noise pollution (> 40dBA) in protected and silence zones;
- Air pollution (NOx) due to private vehicles on motorways.
The single run is not what counts:
Working with uncertainty
Probability that the cell is occupied by particular land use as the result of uncertainty in parameter(s).
Not 1, but 10, 100, …, runs Fluctuating 1, 2, …, all parameters

Milieu- en Natuureffecten Nota Ruimte
RIVM, May 2004
Prepared for VROM (Ministry of public housing and Spatial Planning and the Environment)
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.
- Validation period(s): 1996–2000; 1989–2030;
Stepwise Calibration procedure

Modular model enables use of modular calibration routines

- One main disadvantage:
  - Essential feedbacks get lost when calibrating coupled models
- Many advantages:
  - Model specific calibration techniques and tools;
  - Emphasis on model specific parameters;
  - Model specific GOF and analysis;
  - Reduction of processing time.

Iterative process
- First decoupled: use stored time series, then coupled: use model output
- First Local (cellular), then Regional, then coupled
Objective function Regional model

*Van Loon, 2004*

\[
\begin{align*}
\text{Minimize } & \sum_{K=1}^{\text{Nr Sectors}} \sum_{i=1}^{\text{Nr Regions}} \left( W_K \cdot W_\beta \cdot \left( \frac{X_{\text{ref}Ki} - X_{Ki}}{X_{\text{init}Ki}} \right)^2 + W_\delta \cdot \left( \frac{W_{\text{ref}Ki} - W_{Ki}}{W_{\text{init}Ki}} \right)^2 \right) \\
\end{align*}
\]

- Minimize error
- Emphasis on sector(s)
- Emphasis on two parameter sets:
  - ‘Attractiveness parameter set’
    - Parameters influence 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 selective optimization
  - Where are the major errors in the simulated maps?
  - Which can be solved?
  - Which adjustments will be successful?

- Adjusting the rules:
  - 'turn the model inside out'
  - What should have been the correct land use?
  - hence, the transition potential?
  - hence, the neighbourhood effect?
  - and hence the interaction (distance decay) rules?

![Graph showing effect of residential on residential with points (0, a), (1, b), (c, d), and (e, 0)](image)
## Results

**Calibration period**

<table>
<thead>
<tr>
<th></th>
<th>Local scale Fuzzy Kappa [-]</th>
<th>Regional scale Activity [% growth]</th>
<th>Regional scale Area [cells]</th>
</tr>
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<tr>
<td></td>
<td>EE</td>
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</tr>
<tr>
<td>1989–1996</td>
<td>0.94</td>
<td>3.9</td>
<td>3.3</td>
</tr>
<tr>
<td>1996–2000</td>
<td>0.91</td>
<td>5.2</td>
<td>7.7</td>
</tr>
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**Validation period**
Interpretation of Results:

- 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]

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- 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?
Influence of quality of the data

- Dominant land use at 500 m resolution
- “Dubious land use changes”

Surface waters in North-Friesland

1996

- Agriculture
- Greenhouses
- Urban
- Nature
- Recreation
- Features

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