Cellular automata as the basis of integrated dynamic modeling

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Geog 590-002 Land-Use Modeling - Week 7

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Research Question

- The aim of this application was to demonstrate that an integrated cellular approach is a useful tool for exploring the possible long-term socio-economics impact of climate change in the Caribbean

- The model described here was being calibrated for an application to the Caribbean island of St Lucia as part of a United Nations Environment Program project on global climate change

- A climate model is specified to represent a scenario in which rising temperatures lead to and increasing storm frequency and precipitation, with adverse effects on the level of demand for tourism

Model Methodology

- Cellular automata (CA) are rapidly gaining favor among geographers as a tool for modeling spatial dynamics
  - (since late 1980's; H Couclelis 1985 & 1989 and others)

- Presented is an integrated cellular automation-based model of regional land-use dynamics
  - Spatial: St Lucia (a windward island)
    616 sq km (3.5 times the size of DC)
  - Temporal: 40 years starting in 1990

- A standard CA model
  - Is Not desirable to model land-use dynamics
  - Since it is defined as a homogeneous cell space and unconstrained

Model Methodology (cont)

CA land-use models depend on three factors:

1. The inherent qualities of the land itself
2. The effects of neighborhood land-use activities

   (Standard CA models only deal with the neighborhood effect)
3. The aggregate level of demand for land for each activity

The model presented is a <u>constrained</u> stochastic (random) cellular automation defined on a <u>nonhomogeneous</u> grid space

Model Methodology (cont)

The model consists of three linked components:

1. A **GIS** which stores relevant spatial data on land use and suitabilites for various land uses

   (A CA can be thought of as a GIS with a dynamic defined on it)

   (This model's GIS operations are performed in IDRISI)

2. A **cellular automaton**, which represents the local spatial dynamics inherent in the system, with cell states representing land use or land cover

3. A **macro-scale model** representing the non-spatial data on the population, the economy, and relevant aspects of the natural environment

Cellular Automation (2nd model component)

- In this model: Each cell represents a land-use subdivided into two categories: Functions and Features
- Functions are those land uses which are active, such as housing forestry, or commerce and can be converted (transformed)
- Features are those land-uses that are fixed, such as water, parks or airports and can not (normally) be transformed, but do influence neighboring cells

Cellular Automation (cont)

- Standard CA neighborhoods are
  - 4 cells adjoining the sides of a given cell (von Neumann neighborhood)

    (The first cellular automation was conceived by von Neumann in the late 1940's)
  - 8 adjacent cells (Moore neighborhood)
- Our integrated CA Model neighborhood consists of <u>113 cells</u>
  - All cells within a six cell radius of the given cell
  - At St Lucia the cell size is 250 meters; cell area = 0.625 sq km

    About 2 _ football fields square
    Neighborhood radius is 1.5 kilometers; full neighborhood area = 7.065 sq km
    Giving St Lucia approximately 9,832 cells
  - On a regular grid there are 18 discrete distances within the neighborhood (?)

Our Model's CA Math

Actual cell land-use in 1990 is given as the initial state

For each active (function) cell, a vector of potentials is then calculated

- Depending on 3 factors

1. The intrinsic suitability of the cell itself as calculated in the GIS
2. The aggregate effect of the 112 cells in the neighborhood
    - Key Factor – depends on the neighborhood cell's state and location
3. A stochastic perturbation

Cells are ranked starting with the highest potential either between cells or functions based on productivity (the price of the land)

- Each active cell is converted to the state for which its potential is the greatest - The transition rule
- Number of cells for each function is contrained by the demand
- Because of the complexity there are very few transitions in this model

Macro-scale Model (3rd model component)

Consists of three linked sub-models:

1. A natural environment model
   - This accounts for ecological/biophysical processes
   - Cell changes generated directly

2. A demographic model
   - Cell changes linked to economic model

3. An economic input-output model
   - Cell changes linked to demographic and natural environment models

Note: Demographic and Economic models have a relationship of mutual causation

Verification, Validation & Calibration

- This integrated cellular model was Verified and Validated for the city of Cincinnati Ohio by our authors White & Engelen in a 1994 article:
  - “Urban systems dynamics and cellular automata: fractal structures between order and chaos”, *Chaos, Solutions and Fractals* 4, pp 563-583
- A Sensitivity Analysis Validation to see if the integrated components tend to constrain each other so together they give realistic results based on a ‘generic’ small Caribbean island was completed by Engelen
  - “Exploring modeling of socio-economic impacts of climatic change”, *Climate Change in the Intra-Americas Sea*, 1993
  - ‘Numerical modeling of small island socio-economics to achieve sustainable development”, *Small Islands, Marine Science & Sustainable Development*, 1996
- The model was Calibrated on a simplified version by White
  - “The use of constrained cellular automata for high-resolution modeling of urban land use dynamics”, *Environment and Planning B: Planning and Design* 24, forthcoming, 1997

Exogenous (Input) Data

- GIS model actual 1990 physical data
- Natural environment model
  - Linked to the effects of global mean temperature change
    - Linked to precipitation, storm frequency and sea level
      - Precipitation impacts agriculture production
      - Storm frequency impacts tourism
- Demographic model
  - Linked to population growth, mortality and migration
    - Without considering age or sex
- Economic model
  - Linked to agriculture, industry, trade, services, tourism, local demand consumption, and exports (primarily bananas)

Endogenous (Output) Data

Initial Cell Changes (from / to)

- **Land Use**
  (Human occupancy)
- Fixed Features
  - Airport
- Active Functions
  - Agriculture
  - Mixed Agriculture
    (20% - 70% secondary forest)
  - Rural Residential
  - Tourism
  - Urban

- **Land Cover**
  (Natural land uses)
- Fixed Features
  - Beaches
  - Mangroves
  - Primary Forest
- Active Functions
  - Secondary Forest
  - Scrub and Grass

St Lucia – Demographic / Economic Data

	1990 actual (St Lucia Gov't)	2002 actual (CIA factbook)	2030 est (Model)
Population	134,000	160,145	190,000
Birth rate (per 1000)	26.9	21.37	16.7
Death Rate (per 1000)	6.3	5.3	5.4
Migration (net) (per 1000)	-5.8	-3.64	
GDP	US $1049 M	US $ 700 M	
GDP Per Capita	US $ 7,828	US $ 4,400	gloomy
Unemployment		15 %	higher

St Lucia - Geography

- Political Part of British Commonwealth (under control since 1814)
- Physical
  - 616 sq km 3.5 times the size of DC
  - Southern area humid tropical
  - Central area Mountainous – 3000 ft peaks
  - Northern semi-arid
  - International airport – southern end 1.5 hours drive to main resort area
  - Smaller airport – near resort area (requires connecting flights)
  - Good beaches and water sports
  - Ecologically diverse
- Economic
  - Agriculture 8 % bananas – imports reduced by EU & Lat Am competition
  - Industry 20 %
  - Services 72 % primarily tourism

Authors Interpretation of Output

- The most valuable aspect of CA-based modeling is that it permits socio-economic models to be integrated in a detailed and relatively realistic way with models of the natural system, so their joint behavior can be explored
- In the case of St Lucia, a country with essentially no buffer between itself and events in the world economy, forecasting beyond the very short term is clearly impossible
- Running the model for 40 years gives gloomy results
- Economy does not do well – unfavorable tourism outlook
- Employment falls after growing for 1st 25 years
  - Natural environmental constraints restricts agricultural growth
- Changes in land-use are not dramatic because of strong topographical and climate constraints
  - Only some scrub and grass areas convert to agriculture

Authors Interpretation of Output (cont)

- What the model can do is support ‘what if’ experiments
- The future is more predictable than might be expected, owing to the presence of **<u>bifurcation</u>** in the system
- Bifurcation => To divide into two branches; fork
  - New and qualitative solutions appear suddenly as one or more parameters pass a critical value
  - The 3 components of the macro-scale model are linear (predictable)
    But, Once linked their behavior becomes nonlinear (unpredictable)
  - Of particular interest to planners are the spatial bifurcations that occur with a dramatic land-use change as a parameter value crosses a critical value threshold
  - Want to know: Is the actual parameter value above or below the critical value

Model Spatially Explicit

- Invariance Test: Yes
  - Workings are affected by randomly moving the objects that participate in the model
- Representation Test: Yes
  - Contiguity relationships of what land use is next to what other land use
- Formulation Test: Yes
  - GIS locations appear directly in the model
- Outcome Test: Yes
  - The model modifies the landscape on which it operates

Weakness - Limitations - Conclusion

- No conclusion on the Global Climate Change Research Question
- Purpose of study appears to be the authors intent to calibrate their model in a different (mixed land-use) environment than in an urban environment (Cincinnati) were it was developed
- No discussion on why they choose the large 113 cell neighborhood
- Authors concluded the model was Not applicable to St Lucia for long term predictions, and then diverted the discussion to bifurcation which confirms Batty's statement in APA Journal Spring 1997 p273

  "CA is an exploratory modeling technique; it is more suited to assessing the effect of simple principles for idealized development rather than it is to full-scale simulation" (such as St Lucia)

Extensions

- Since the St Lucia project was still underway and final calibration had not been completed (when published) was there final project report

- Based on the Cincinnati CA model, reasonable forecasts of urban land-use patterns over a period of 10 – 15 years can be made with some confidence, *If the growth rate of the city is known (*per authors)
  - assume they have done further work since then with their model (such as)

"High Resolution Integrated Modeling the Spatial Dynamics of Urban and Regional", *Computers, Environment & Urban Systems*, 24 5 pp 383-400 (2000)