The research frontier in urban modelling

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- how can we build models of the evolution of cities and regions?
- the essence of the tool kit is there:
  - spatial interaction and location models
    - the fast dynamics
  - models of changing structures
    - the slow dynamics

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- will illustrate the ideas with two examples, one of them subdivided to show different approaches:
  - retail systems – London and South Yorkshire
    - BLV models
    - ABM models
  - a large urban system over a long period
    - the US from 1790-1870

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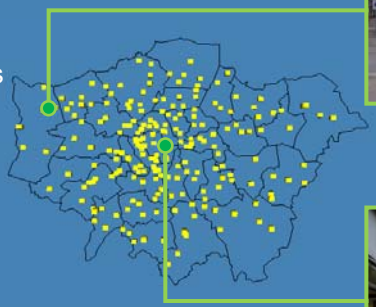
London retail system

- Major city system
  - ~206 retail centres
- Focus on discontinuous change
  - Difficult to predict
  - Large impacts
- Stepping stone to understanding urban evolution



Example suburban high street: **Ruislip**

Example central retail centre: **Oxford Street**

Retail model – spatial interaction

$$S_{ij} = A_i e_i P_i W_j^{\alpha} e^{(-\beta m_j c_{ij})} \qquad A_i = \frac{1}{\sum_k W_k^{\alpha} e^{(-\beta m_j c_{ik})}}$$

- S_{ij} : consumers living in zone i and shopping in zone j
- e_i : average income in zone i
- P_i : population in zone i
- W_j : retail floor space in zone j
- α : impact of retail zone size on consumer decisions
- β : impact of travel cost on consumer decisions
- c_{ij} : travel cost from zone i to zone j
- m_j : public transport multiplier for zone j

Retail model – structural dynamics

$$\frac{dW_j}{dt} = \varepsilon\left(D_j - KW_j\right)$$

- ε : rate at which retail zones respond to profit levels
- D_j : total income of retail zone j
- K : costs per m^2 in retail zone j
- W_j : retail floor space in zone j

Evolving to equilibrium during a single time step

KEY

Retail centre growth

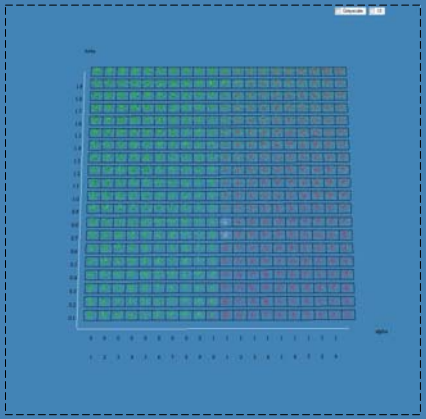
- Growing
- Stable
- Shrinking

Consumer spending flow size

- £1,000
- £10,000
- £100,000
- £1,000,000

Results grid overview

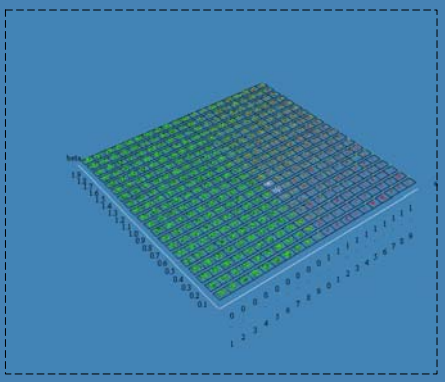
- For a **single time step**
  - vary two parameters over a short range, e.g.:
    - *x* => **alpha:** benefit of visiting a large retail centre
    - *y* => **beta:** Impact of travel cost
  - run the model to equilibrium for each possible combination of model parameters
  - present the results on a grid



Using a results grid to identify discontinuous change

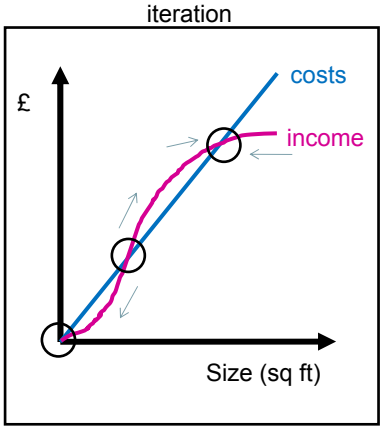
- Use an **order parameter** to summarise the equilibrium structures across the grid
- Plot as surface
- Identify discontinuous change
- And potentially unstable states

Order parameter = spatial spread

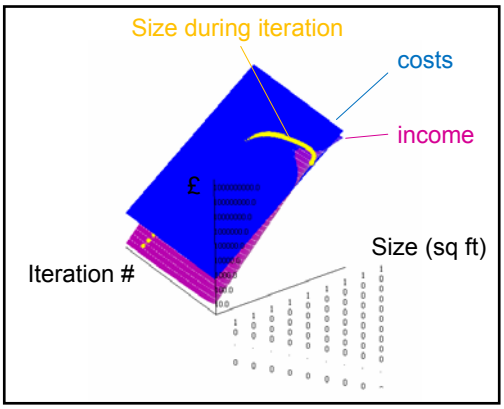


Income-costs zone graph

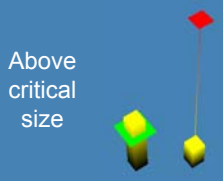
Explains behaviour during one iteration



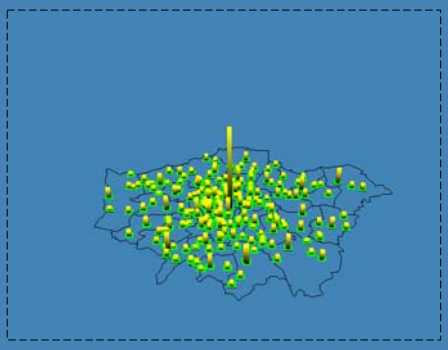
…but changes every iteration



Critical size markers

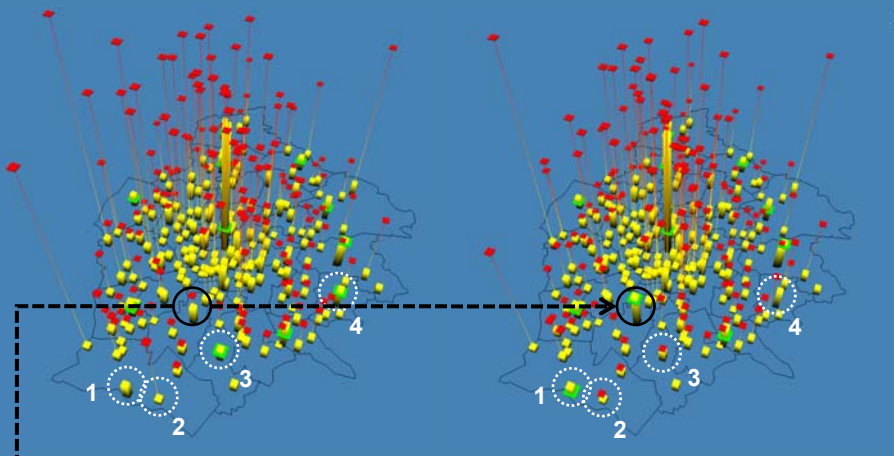


- We are exploring ways to present the critical sizes of all retail centres together



Critical size markers for three different sets of model parameters

Exploring changes in initial conditions



Enlarge Ealing from 130,000 sq ft to 480,000 sq ft

A new idea: DNA and path dependence

$[\{S_{ij}\}, \{W_j\}, \{m_j\}, \{e_i\}, \{P_i\}, \alpha, \beta, \varepsilon]$

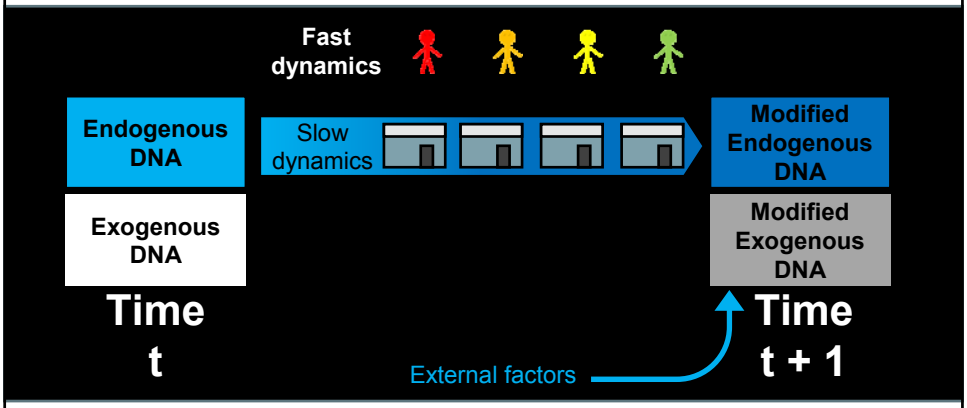
$[\{S_{ij}\}]$ *Endogenous* ***Fast*** *Dynamics*

$[\{W_j\}]$ *Endogenous* ***Slow*** *Dynamics*

$[\{m_j\}, \{e_i\}, \{P_i\}, \alpha, \beta, \varepsilon]$ *Exogenous parameters*

SYSTEM DNA

DNA and evolution



- Each time step produces the "initial" DNA for the next time step

Path dependence in urban systems

- Arthur (1988)
  - Agglomeration economies
  - Multiple system “solutions”
  - Chosen by unpredictable, apparently “insignificant” events
  - Magnified by **positive feedbacks**
- Here we define path dependence as:
  - Sequence of initial conditions / initial DNA
  - Each influences possibilities of development
  - Basins of attraction within reach

Challenges for forecasting

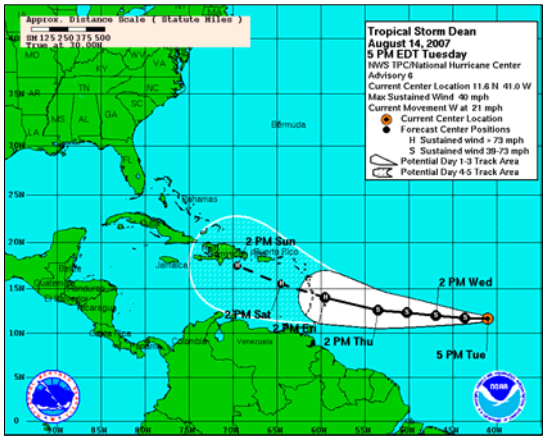
- Large number of interacting parts
  - Nonlinear relationships
- Emergent behaviour
- Path dependence
- Computational challenges of modelling and simulation
- Discontinuities

Hurricane forecast tracks*

•5-Day Track Forecast Cone forecast

•uncertainty is conveyed by the track forecast "cone“

•Can we produce a similar possibility-cone for an urban system?



Source: National Oceanic and Atmospheric Administration

An urban possibility-cone

- Many potential future variations in “initial DNA”
- Diverging **possibility-cone** of development path
- Cone should **contain** future state

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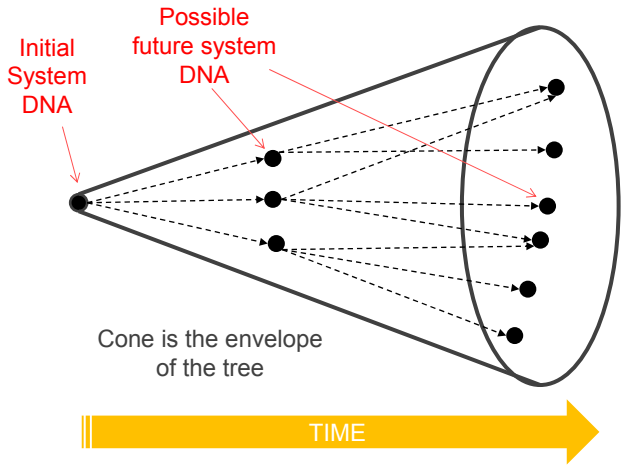
Building a possibility-cone: structure



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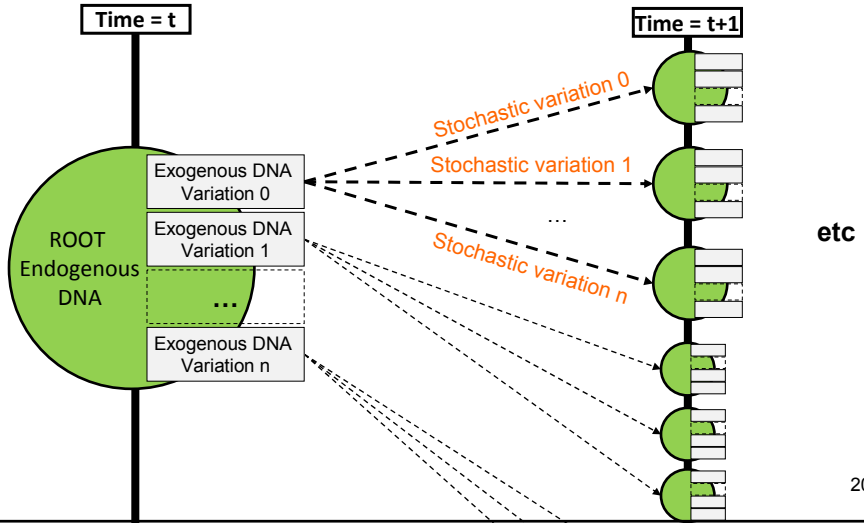
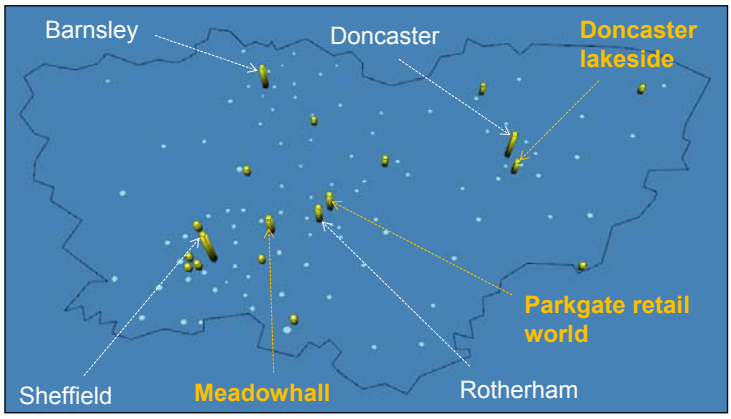
Branching



South Yorkshire example: root DNA

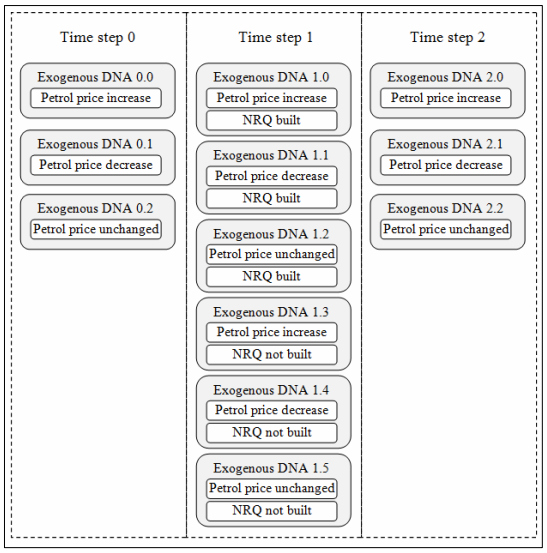


Examples of possible future events

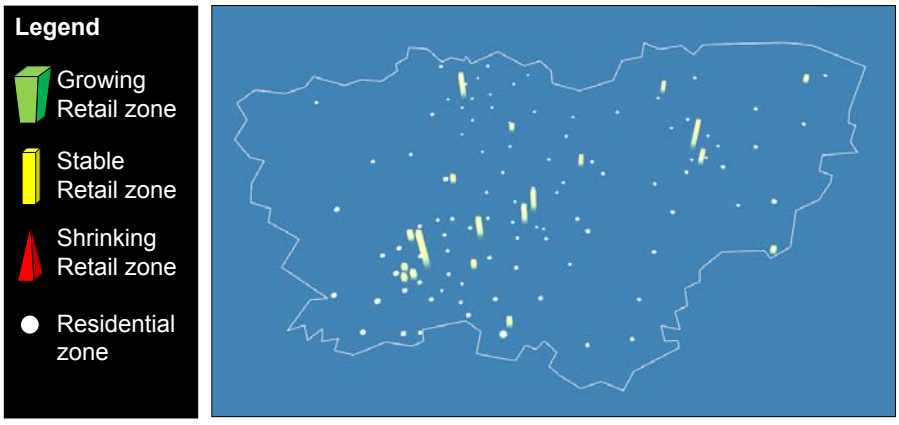
Event	Type	Possible outcomes	Time step
Fuel price fluctuation	Unplanned	1. Increase 2. Decrease 3. Unchanged	Any
Shopping centre construction	Planned	1. Built 2. Not built	1

Exogenous DNA variations

- Generate all permutations of feasible future events
- Lots of "*What if*?" scenarios



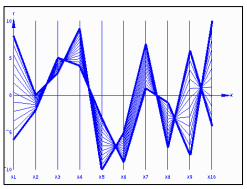
South Yorkshire model run



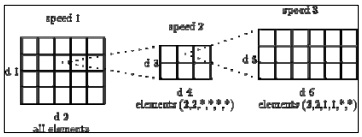
Dimensions and data

- South Yorkshire cone exists in 19-dimensional state space
- Lots of data
  - 19 retail zones
  - 200 iterations per model run
  - Hundreds of model runs
- Information visualisation helpful
  - Easier interpretation of results

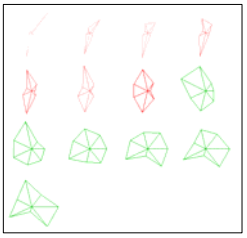
N-dimensional visualisation techniques



Parallel Coordinates
(Inselberg 1985)



Dimensional Stacking
(LeBlanc, 1990)



Star Glyphs
(Siegel, 1972)

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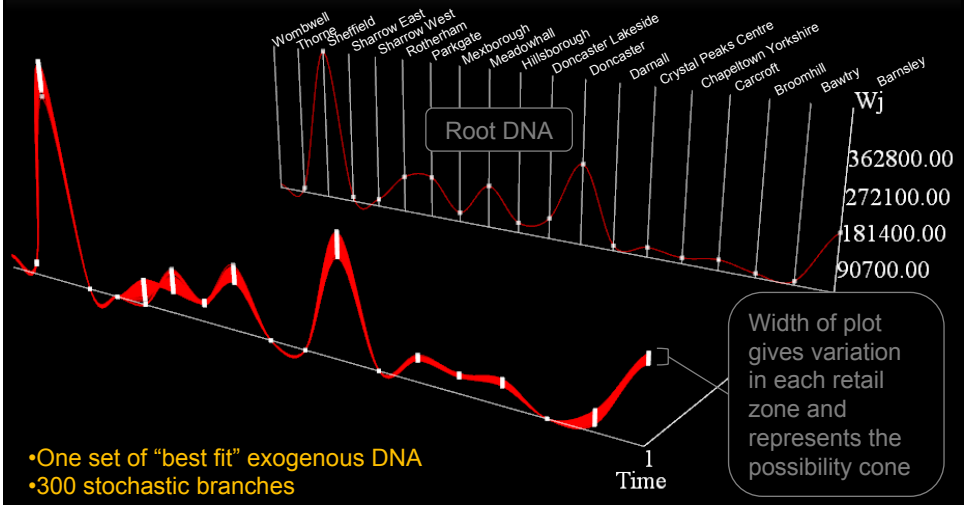
A simple possibility cone



Width of plot gives variation in each retail zone and represents the possibility cone

- One set of "best fit" exogenous DNA
- 300 stochastic branches

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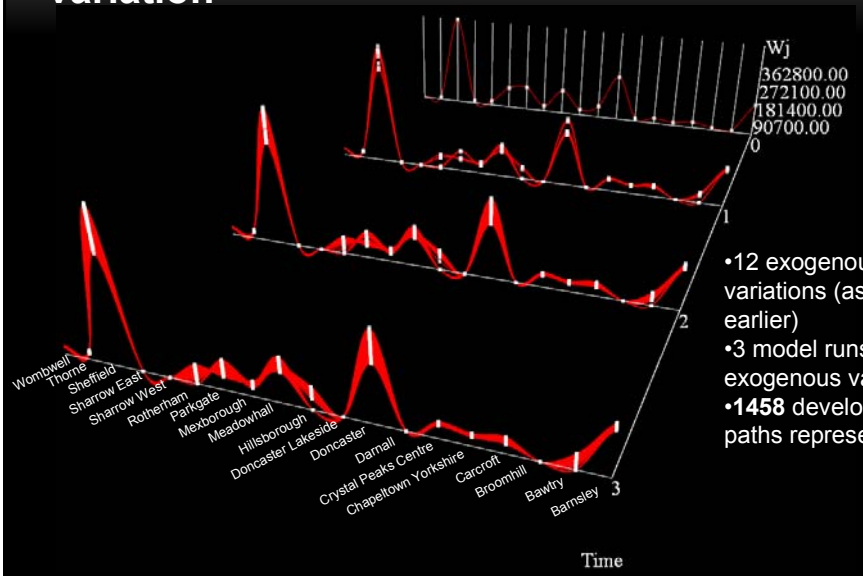
South Yorkshire : multi-step with exogenous variation



- 12 exogenous variations (as defined earlier)
- 3 model runs per exogenous variation
- **1458** development paths represented

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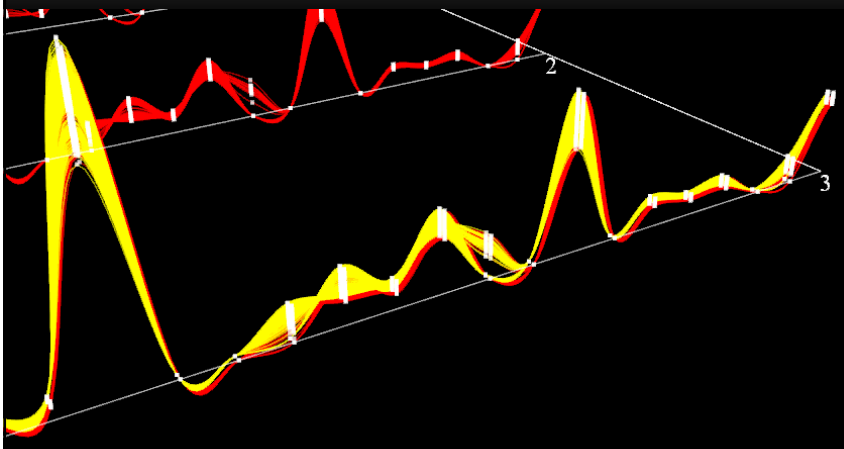
Animated possibility cone



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Urban "genetic medicine": Rotherham

- Extend the DNA idea to "genetic medicine"
- Rotherham town centre is in decline
  - 30% of high street boarded up in March 2009
  - Competition with out of town shopping centres
- What changes do we need to make to the DNA that ensures this centre is more stable?

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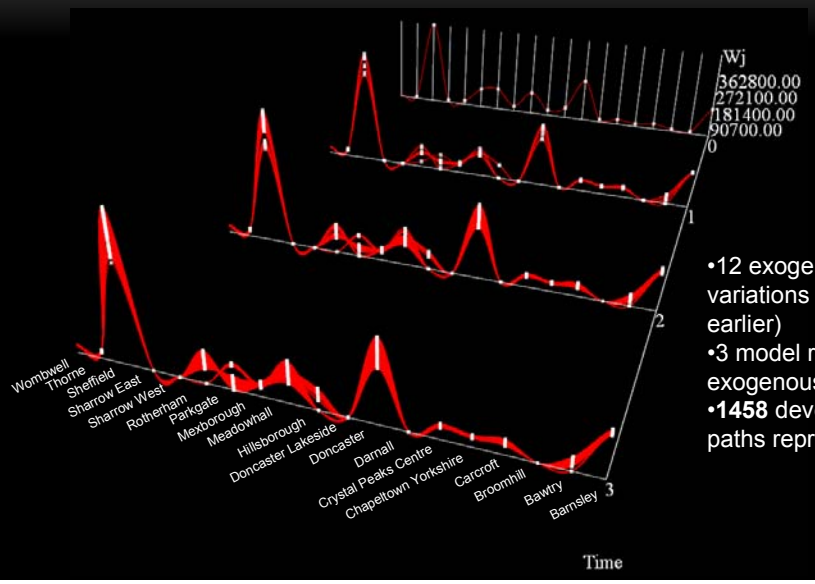
Improved public transport to Rotherham



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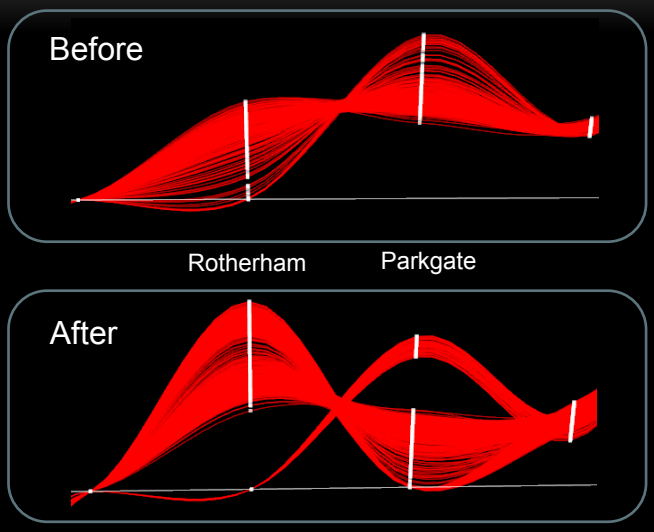
The result of intervention



- A possible approach to be adopted by planners in a complex world
- Forecasting that takes into account inherent uncertainty in future
- Computationally intensive
- Adaptable to other models

Agent based modelling approaches

- Possible to make ABM equivalent to any BLV model?
- How can BLV models inform development of rules for ABMs?
- Retail agent based model
  - South Yorkshire (population approx. 1.2 million)
  - Agents:
    - 500 independent retailers (each owning a single shop)
    - 50,000 consumers (mini-aggregation: 24 people represented by each agent)

Model iteration steps

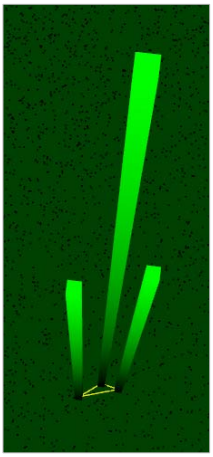
1. Each consumer **chooses** a shop and spends all their money there
2. All shops calculate **profits**
3. ε% of shops **relocate**
4. All shops recalculate how many other shops **nearby** (R_j)
5. Size (W_j) and position of emergent retail zones is detected
6. All consumers recalculate their probability set (p_{ij})

Shop relocation

- Only relocate if not making a profit
- Equal chance of
  - relocating to random position
  - or near competitor - more likely to relocate near one making lots of money

Detecting emergent retail centres

- Near = walking distance (200m)
- We detect closed groups of shops where each member is near to at least one other member of that group
- We consider each group a separate emergent retail centre
- A group of three shops showing **retail centre boundary ➔**



Probability of consumer *i* visiting shop *j* *(two alternative versions of the model)*

Alternative 1

$\mathbf{R_j}$ = Number of other shops within walking distance of j

$$p_{ij} = \frac{R_j^{\alpha} e^{-\beta c_{ij}}}{\sum_k R_k^{\alpha} e^{-\beta c_{ik}}}$$

Alternative 2

$\mathbf{W_j}$ = Number of shops in same emergent retail centre as j

$$p_{ij} = \frac{W_j^{\alpha} e^{-\beta c_{ij}}}{\sum_k W_k^{\alpha} e^{-\beta c_{ik}}}$$

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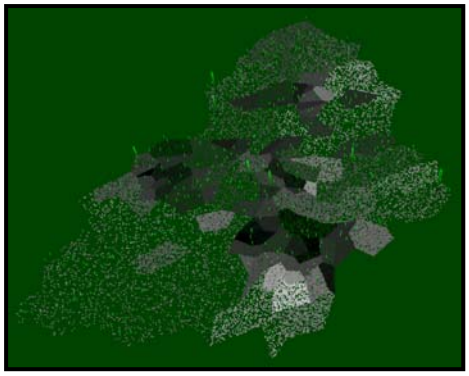
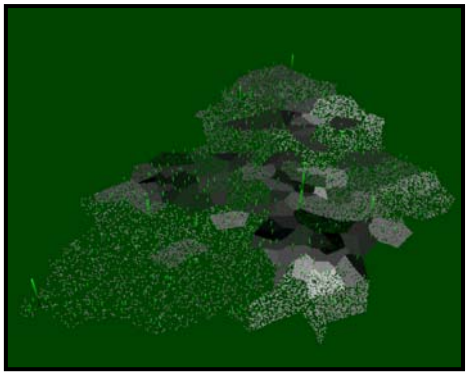
Emergence of structure

R_j function



W_j function



- Start with random uniform distribution of shops
- Consumer agents generated from 2001 census data + CACI paycheck

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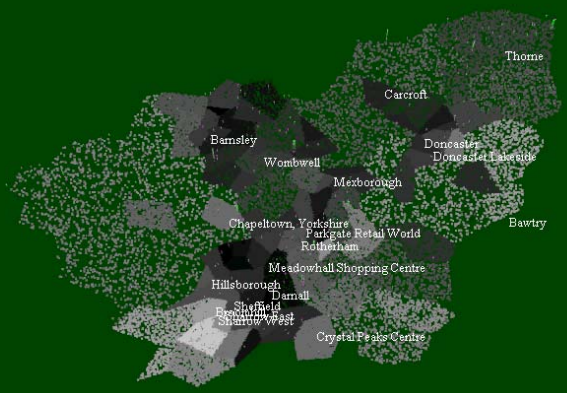

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EXPLORING THE NINETEENTH CENTURY EVOLUTION OF CHICAGO

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Model overview

- An urban retail model translated to system of cities scale
- Added population dynamics
  - Economic migrants
  - Natural population growth
- A spider network represents the transport network

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Model area and period

- East coast to Midwest
- 1790 to 1870
- Focuses on the development of Chicago as the major city in the Midwest

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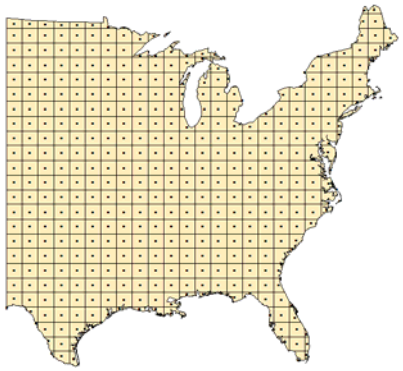
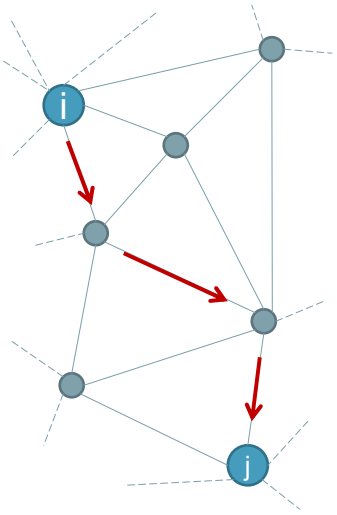
Data for calibration



- Population data at county level from historical census (1790 to 1870) – source: NHGIS (www.nhgis.org)
- County boundaries change each decade
- Aggregated to a regular grid
- 434 cells
- Aggregated “settlements” are grid square centroids

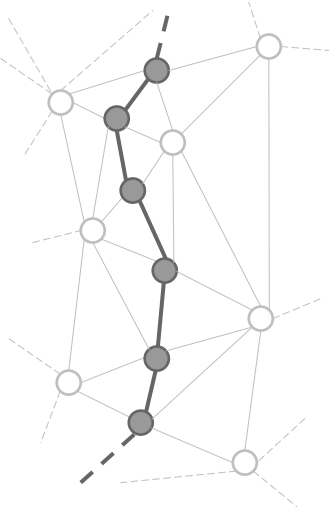
Spider network

- We use a spider network to represent the transport system
- The travel cost from settlement i to settlement j is then the cost of shortest path through the spider network
- When railways construction occurs (either exogenously or endogenously) the link costs change and the shortest paths are recalculated.



Spider network construction

- The spider network was generated by calculating a Delaunay triangulation of the settlement centre points
- Additional links were added to represent:
  - Lakes
  - Rivers
  - Coastline
  - Railways



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Railroads can be introduced in two different ways:

(1) Endogenously

- Land link weights are dynamically adjusted based on changes in the export load flowing over that link
- We use the dynamics equation:

$$\Delta c_{ij}(t, t+1) = -\xi[S_{ij}(t+1) - S_{ij}(t)]S_{ij}(t)$$

(2) Exogenously

- Link weights are reduced along the path of a real railroad at the actual date of construction
- Railway construction data from:
  - Railroads and the Making of Modern America (http://railroads.unl.edu/)
    - KML data
    - Google Maps timeline (1840 to 1870)

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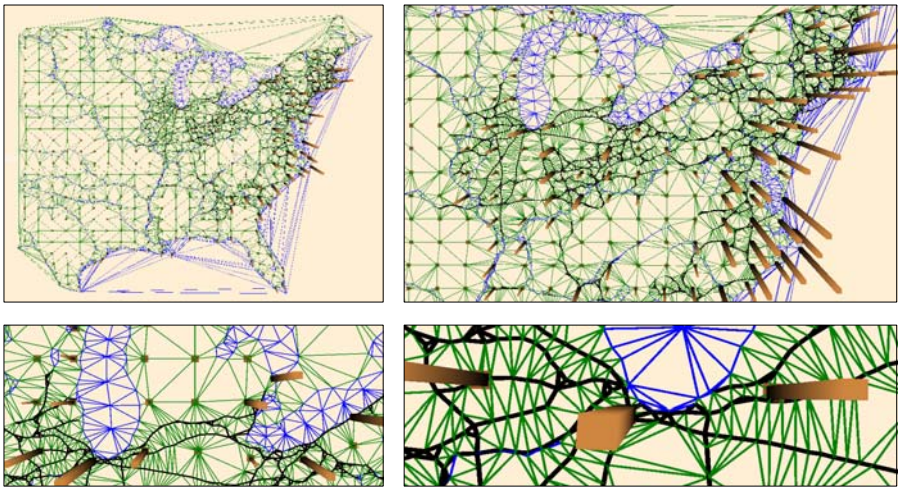
Detail of the spider network for 1870 with land, water and railroads



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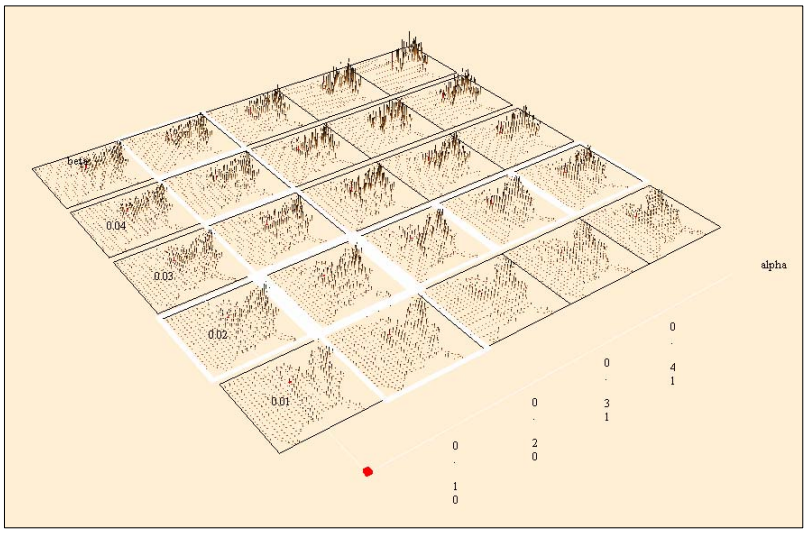
Results grid in [α, β] space



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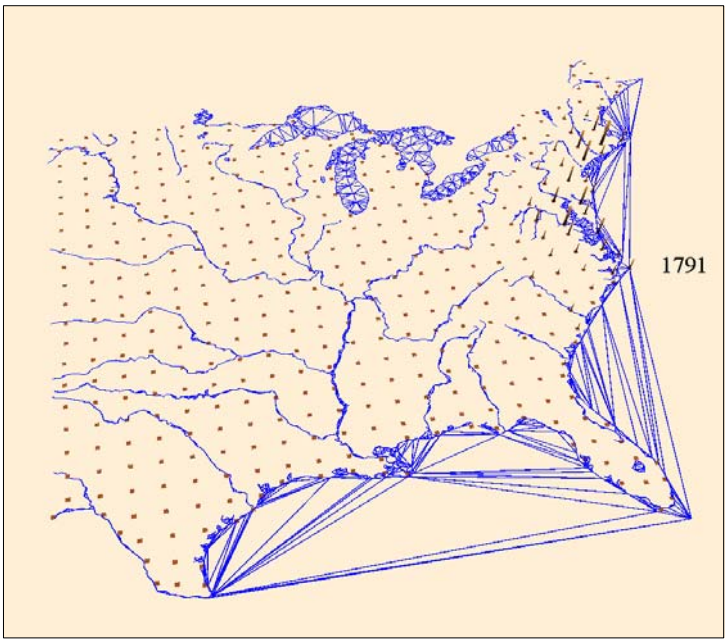

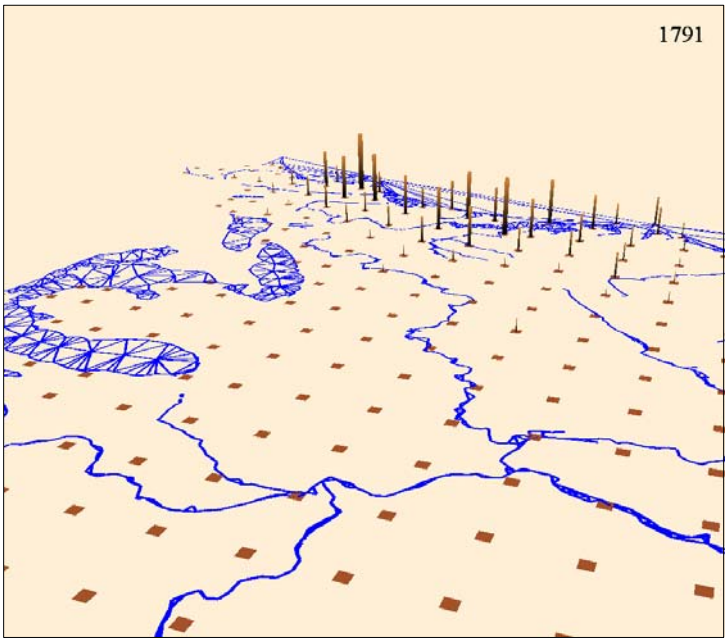
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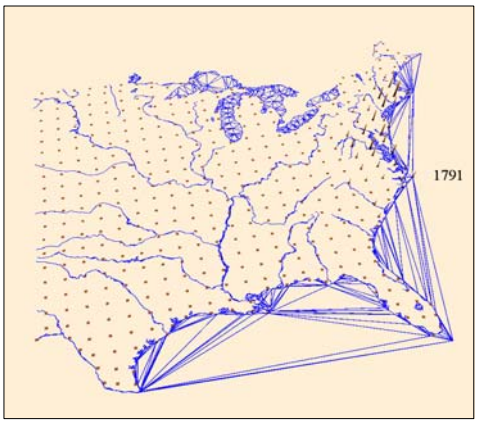
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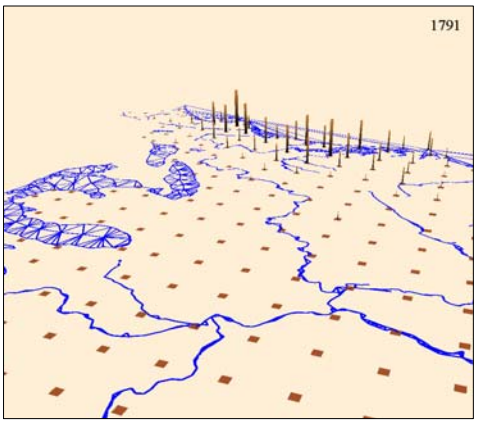
1791

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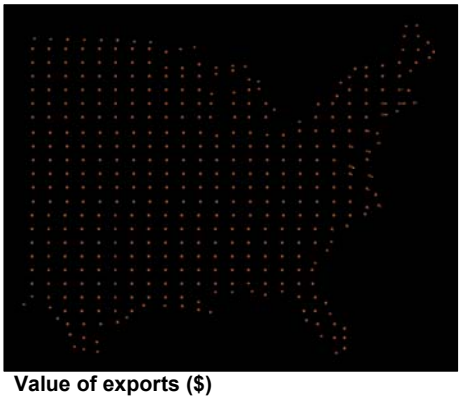
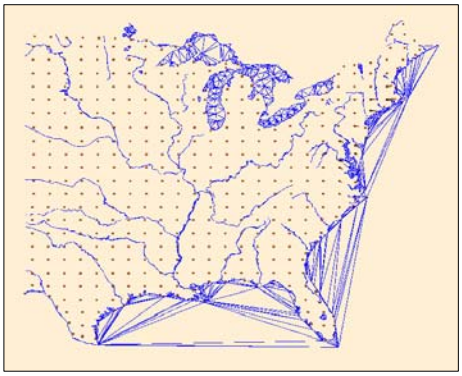
Best fit 1791 exports from Chicago

Exports



Transport network



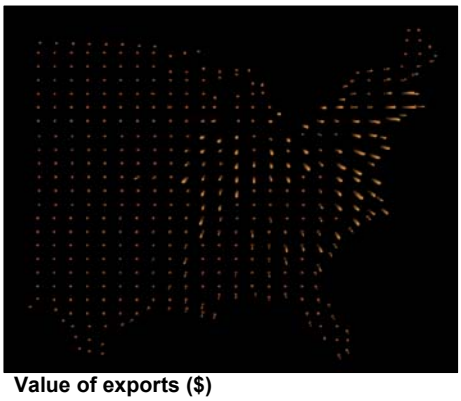
Value of exports ($)

- 0 to 10
- 10 to 100
- 100 to 1,000
- 1,000 to 10,000
- 10,000 +

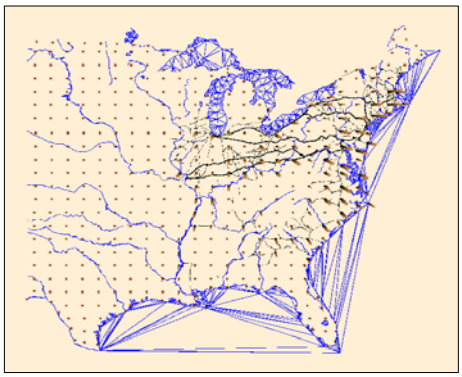
UCL

Best fit 1870 exports from Chicago

Exports



Transport network



Value of exports ($)

- 0 to 10
- 10 to 100
- 100 to 1,000
- 1,000 to 10,000
- 10,000 +

Conclusions

- Railroad development opened up the Midwest
- Without railroads the Chicago site does not appear to be an obvious growth site – so booster marketing and self-fulfilling expectation must have played a large part