The Alan Turing Institute

The future of urban modelling

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1. Urban modelling: then and now

- 1820s: von Thunen: rings of crops round a market town
- 1930s: pre-computers: market areas – Christaller, Reilly
- 1950s – early transport modelling – driven by the highway programme in the US
- 1960s
  - extending to land-use transport models (Lowry, 1964)
  - getting the transport model into good order (e.g. the Newton to Boltzmann shift)
    - A statistical theory of spatial distribution models (1967)
    - Regional Science Association (1967)
  - economic interpretations – CBA etc

- 1970s
  - widespread application of transport and retail models; to a lesser extent, LUTI models
    - some linking to demographic and input-output models
    - overoptimistic on applications
    - New insights in dynamics (Harris and Wilson, 1978)
- 1980s, 1990s
  - slow burn dynamics – Lotka and Volterra applied to cities
  - particularly the implications of nonlinearities:
    - multiple equilibria
    - phase changes
    - path dependence (importance of initial conditions)

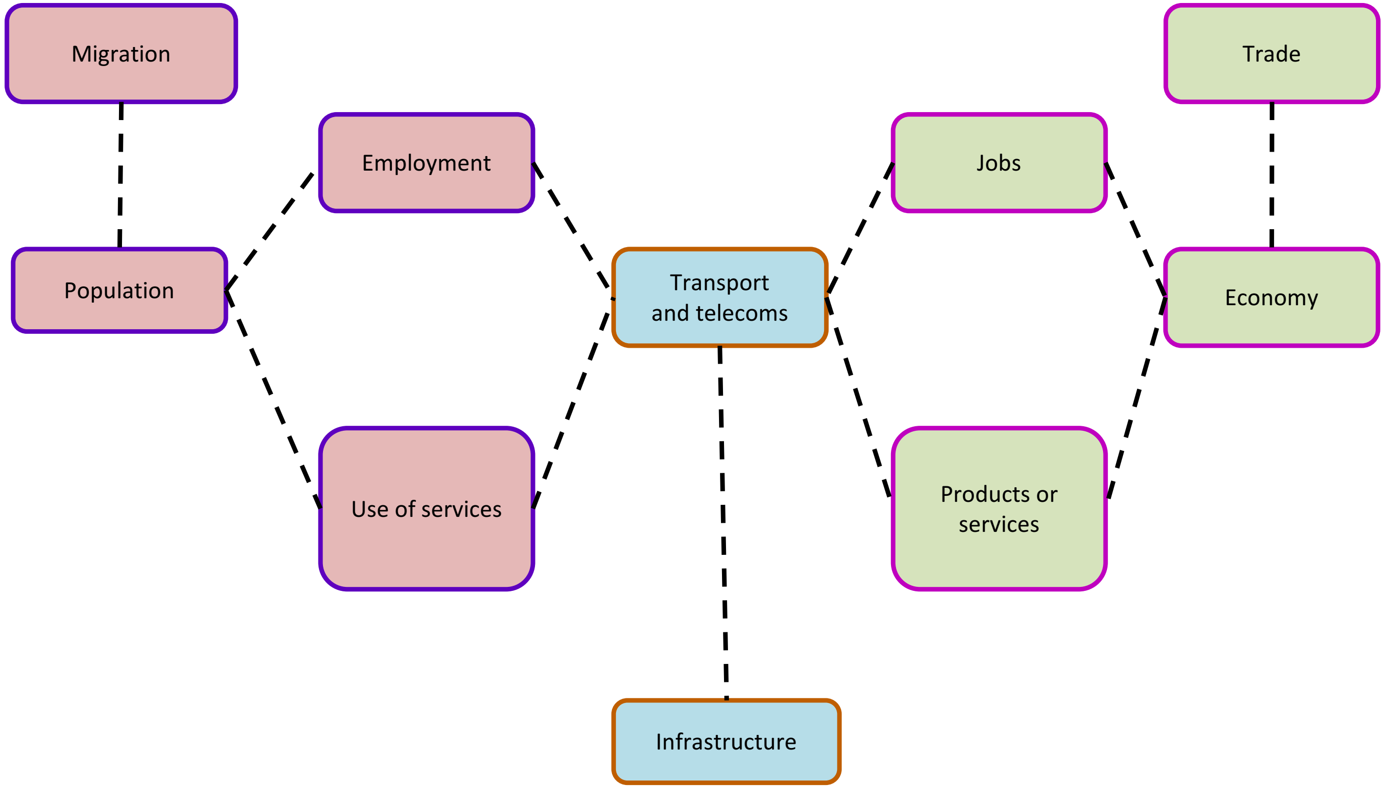
- 2000s
  - increased computing power facilitated the development of new modelling styles:
    - microsimulation
    - cellular automata
    - agent-based modelling
    - network analysis
- new approaches to structural dynamics – (from Turing, 1952)
- forecasting for the short run, scenario exploration for the long run
- competing models? Mostly different ways of making approximations to deal with complexity rather than theoretical differences

- 2010s:
  - and finally, a further step change
    - ‘big’ data
    - increased computing power
- now – towards the 2020s:
  - currently maintained by a relatively small community
  - but ready to grow?
  - new players: Sim City to Improbable? The Venice Time Machine?
  - need to maintain and develop the core

2. Sub systems or whole system?

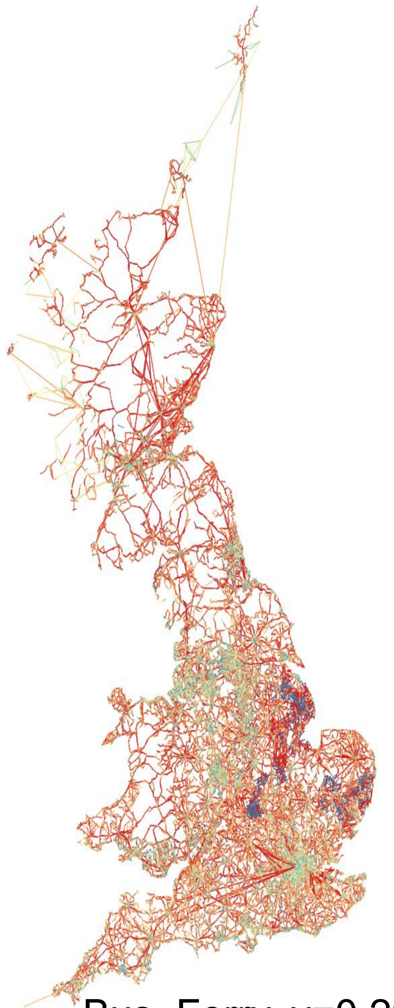
- some subsystem modelling works: transport, retail – at least for short-run planning
- but for exploring urban futures, we have to recognise **interdependence** – and hence the comprehensive, or general, urban model – this should remain our ambition
  - see the Foresight *Future of cities* website
- however, the argument about research priorities can work either way round: model-focused or planning (problem) focused

The comprehensive model

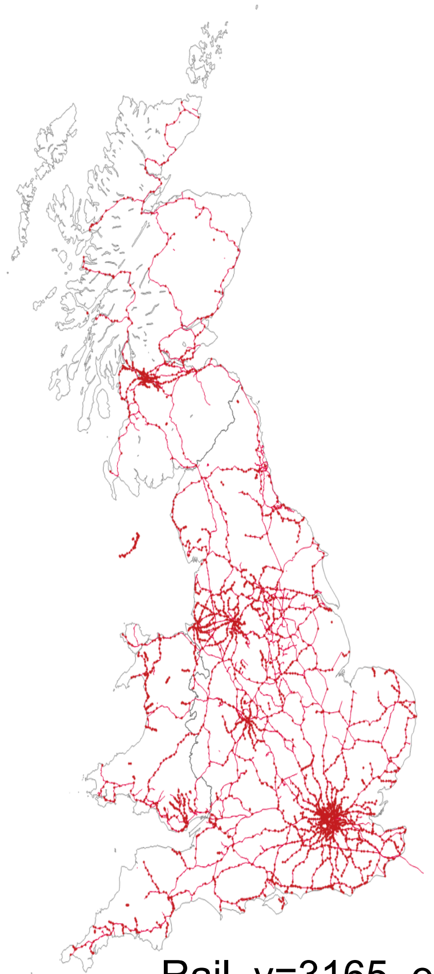


Computing power

Road, v=3.5M, e=8.4M



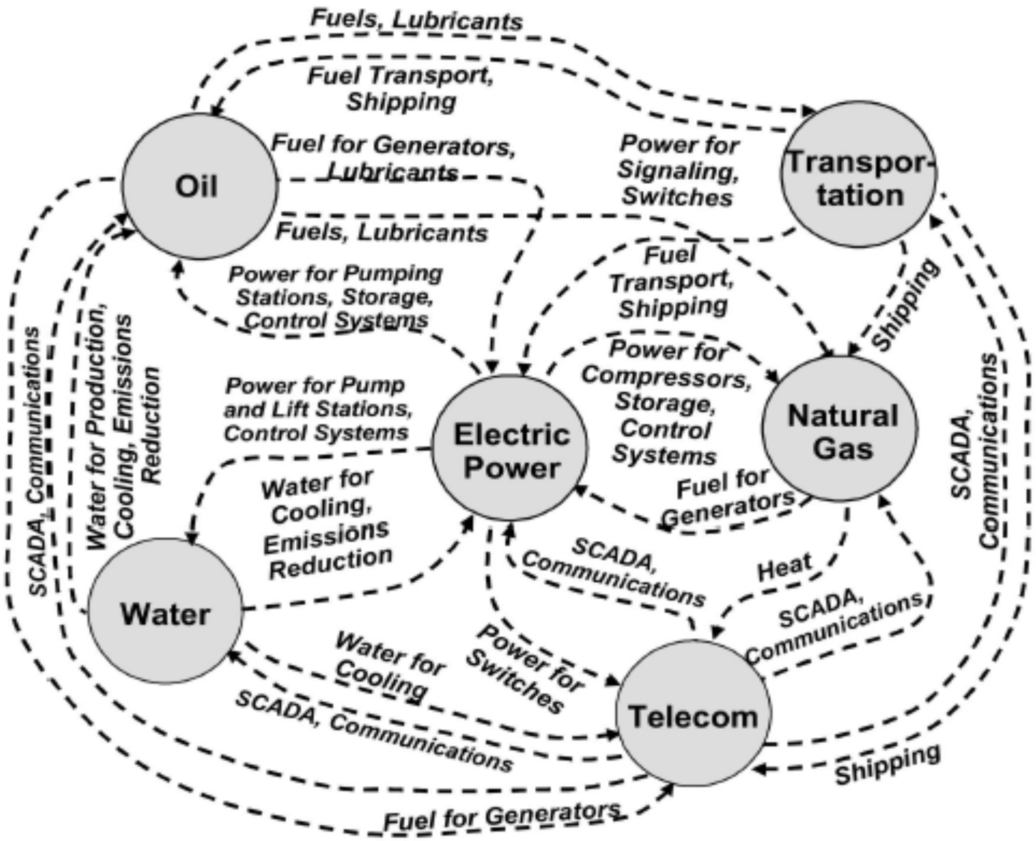
Bus, Ferry, v=0.29M, e=0.42M



Rail, v=3165, e=10,269

Modelling the UK: Quant

The basis for an NIC 'digital twin'?



operational interdependencies between common infrastructure systems

Little, 2005

3. Research priorities: from the straightforward to the very difficult

- making the best of what we have (and extending into new fields)
- dynamics
- finishing off the theory: integrating across paradigms
- new mathematics, new algorithms

- being systematic about the underlying data system and its architecture: data wrangling, matching scales etc
- making good comprehensive models, or submodels, available for applications
- full integration with submodels of the economy and demographics
- extending the range – health, education, defence…..; or by scale (global, regional)
- **illustrate with recent projects: world models, piracy, the London riots**

4. Extending the range - Example 1. The world model

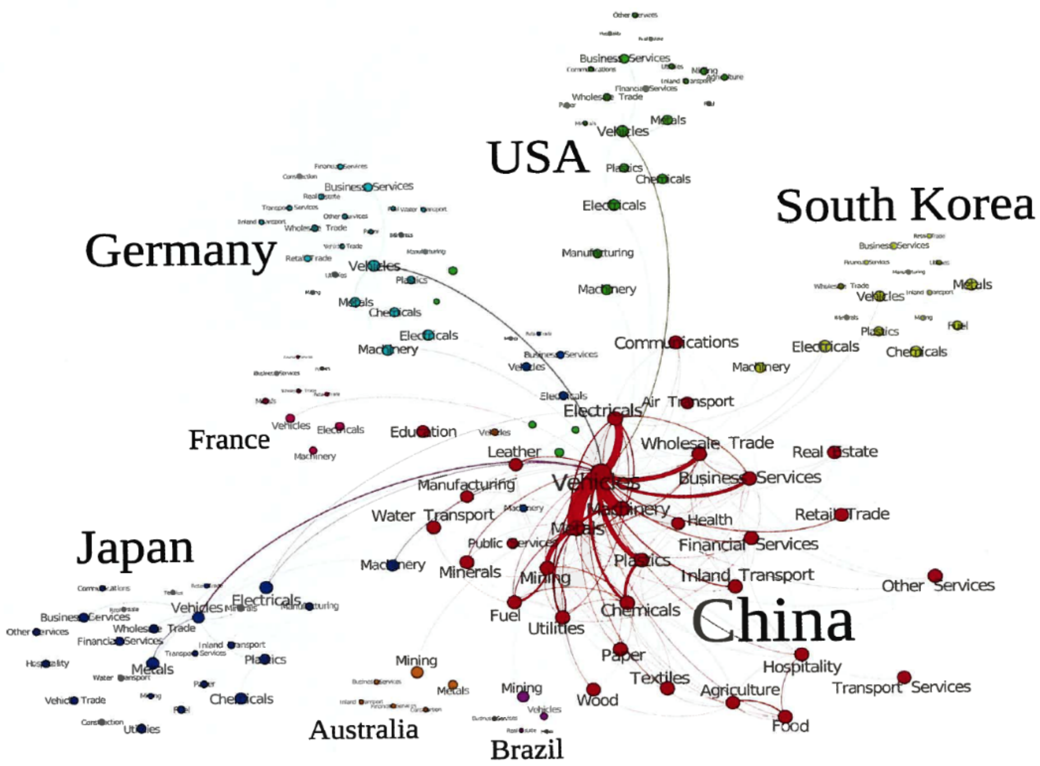


Figure 4.4 A network representation of the seven most-affected countries following a reduction in final demand for the Chinese vehicles sector. Node size is proportional to eigenvector centrality and edge width is proportional to the change in flow. *Source*: Reproduced with permission from Levy et al. (2014)

Example 2. A multi-national trade model: the South Pacific (container services)

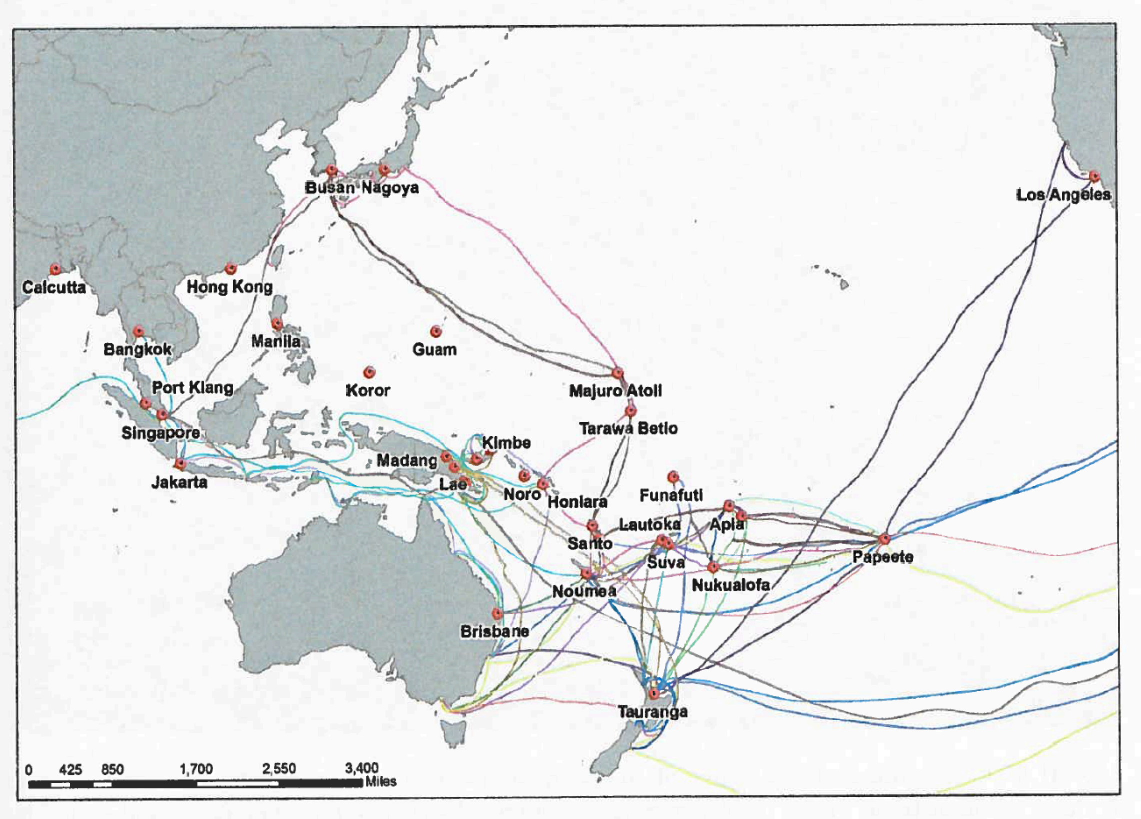


Fig. II.7 Geo-referred visualisation of a sample of 22 container services

The multi-layer model

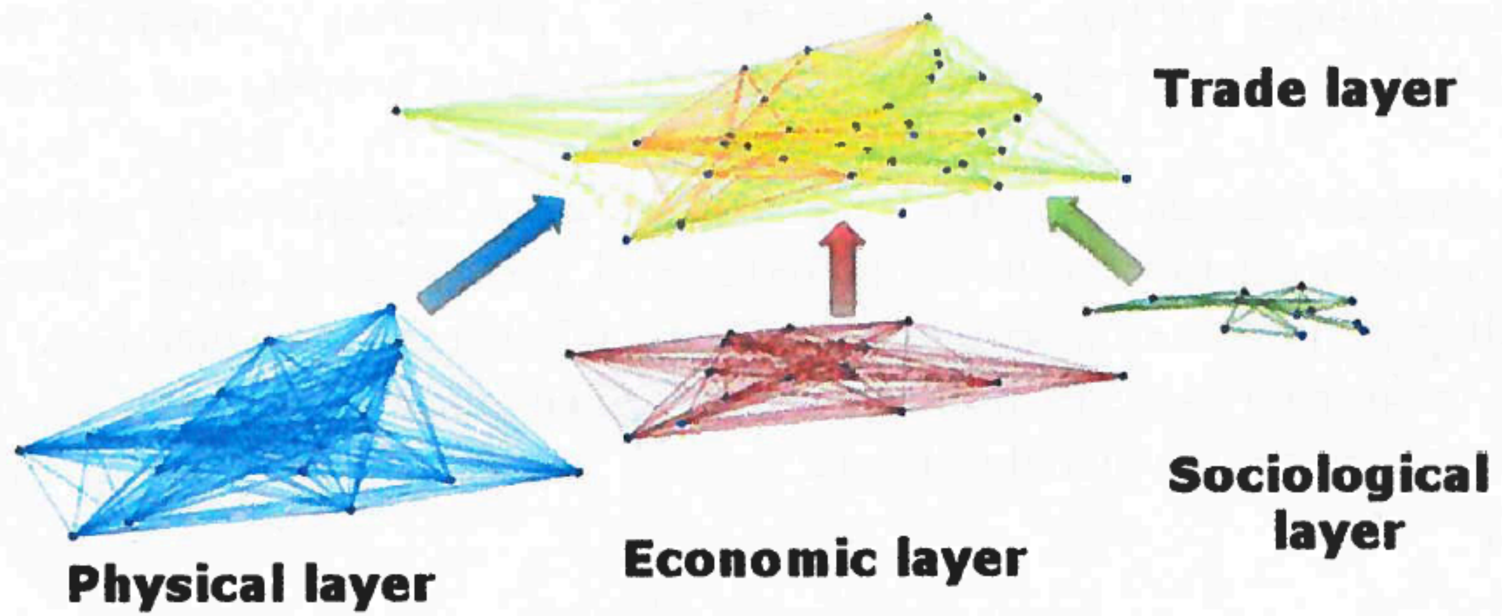


Fig. 2.3 Functional relationships between layers

Principal SPIC trade flows

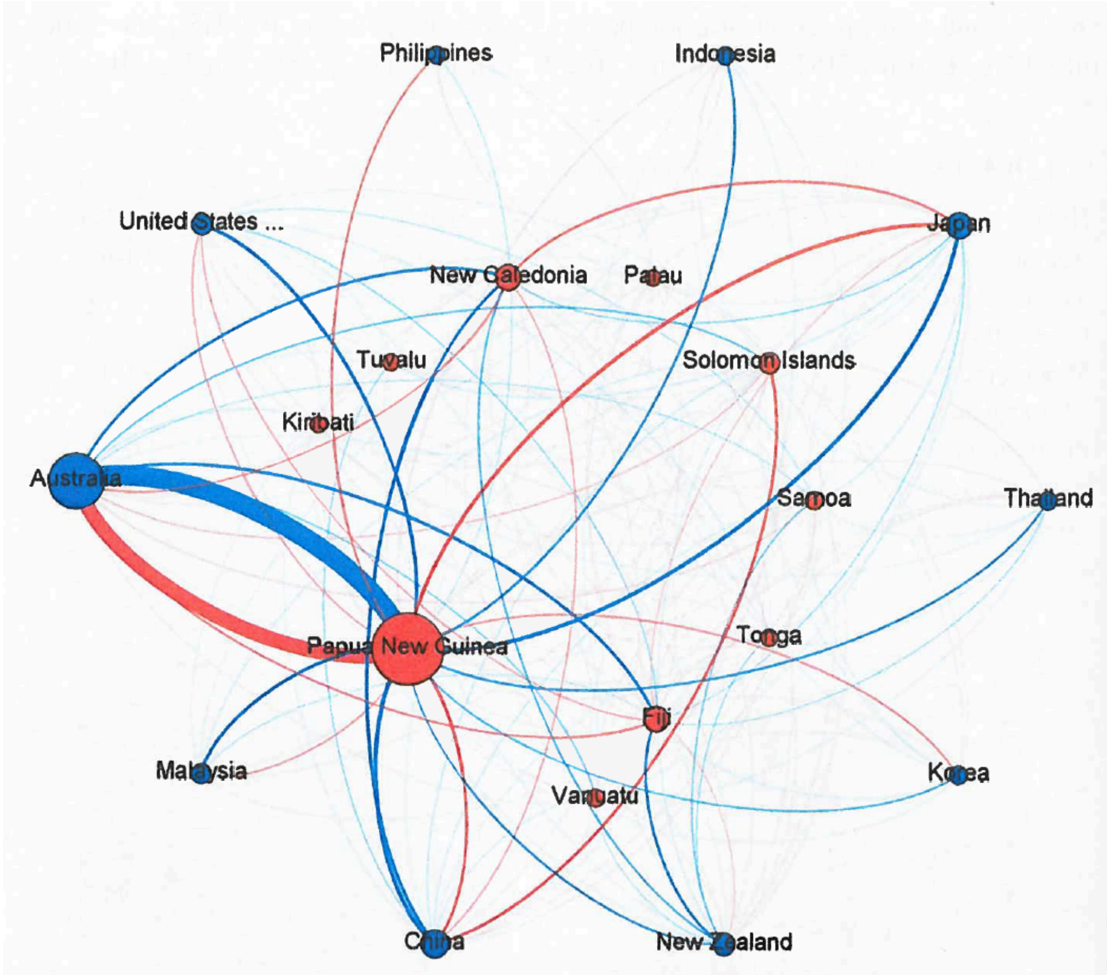


Fig. II.10 Trade flows between countries in the period 2010–2012. SPICs countries are visualised in *red*. Linked colours identify country of origin, and link width is proportional to trade value

SPIC trade underpinned by layers

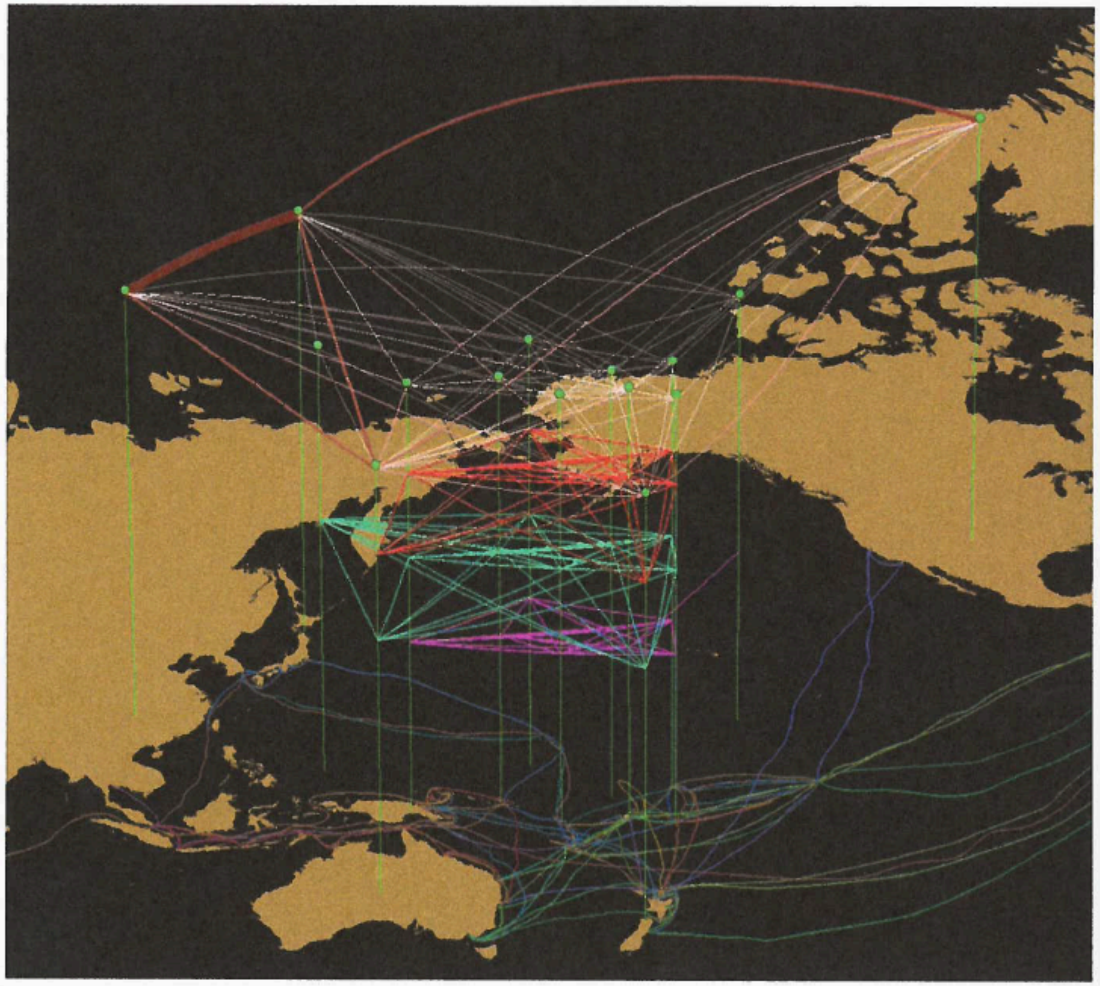
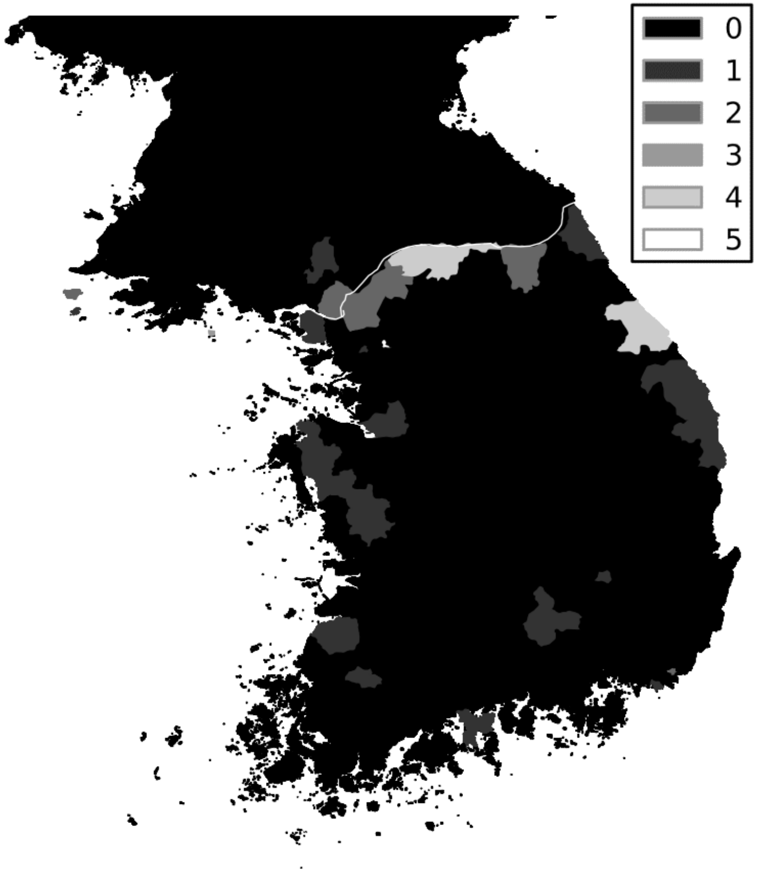
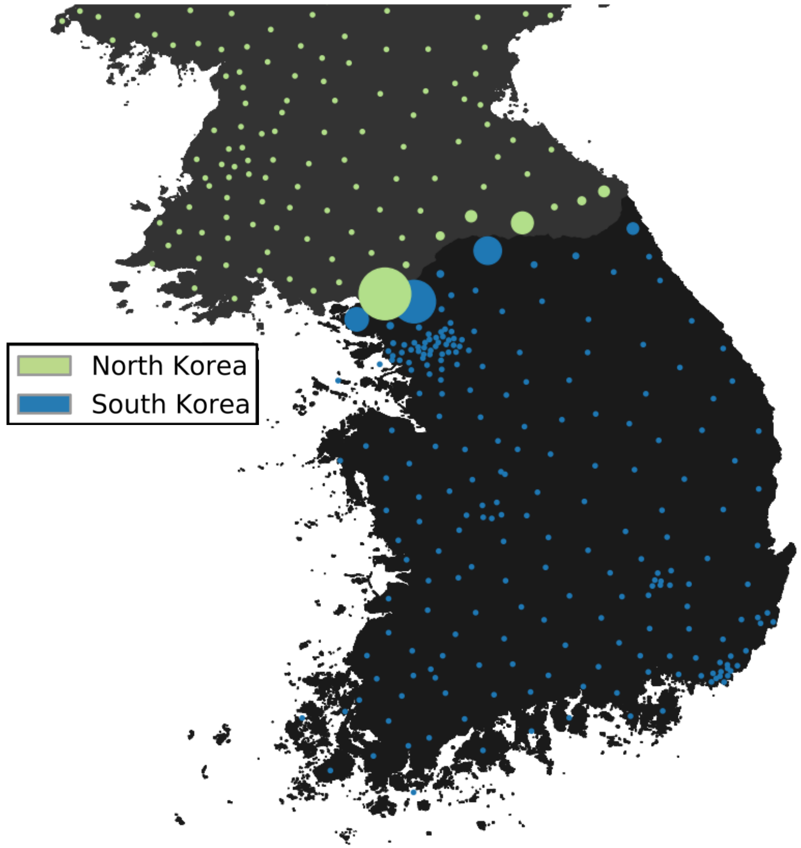


Fig. II.8 A simplified visualisation of the Vertical Interaction model. Depicted from *top* to *bottom*: bilateral trade flows, trade agreements, cultural links, common language, and container shipping network

Example 3. Korean border disputes



Empirical data: Locations of North and South Korean disputes



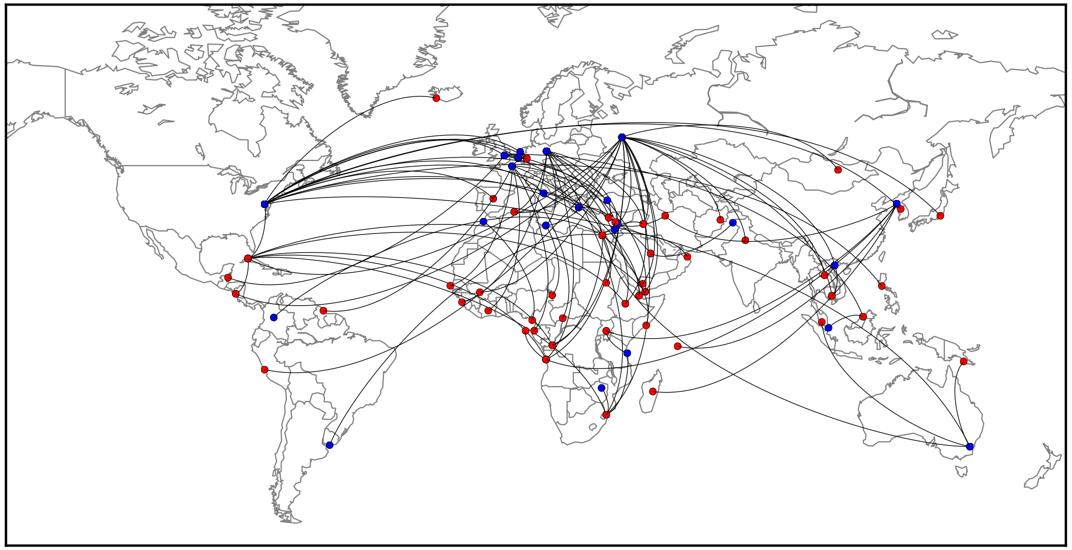
Model data: Equilibrium values of model simulation

Example 4. A global model of military capability

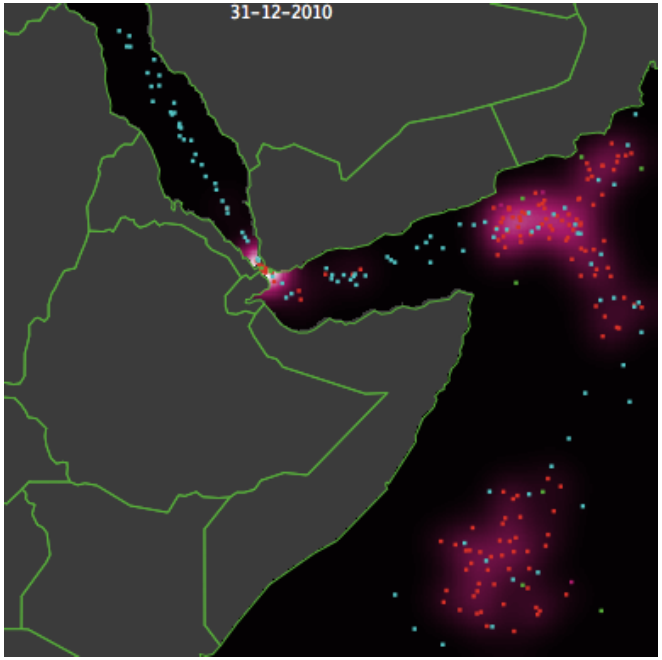
A variation of the model has also been developed to consider how the following three global policy challenges are related to each other, and how they respond in different scenarios:

1. Subnational instability
2. Military capability
3. International alliances

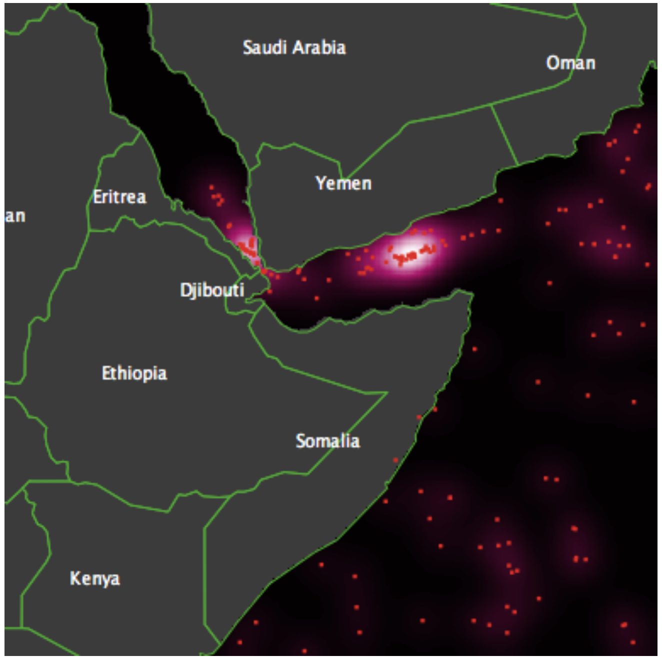
The model will be coupled with a model of global trade to form part of the global demonstration model.



Example 5. Modelling and defending pirate attacks



Simulation results



Observation

• ***Output***: multidimensional density kernel estimator.

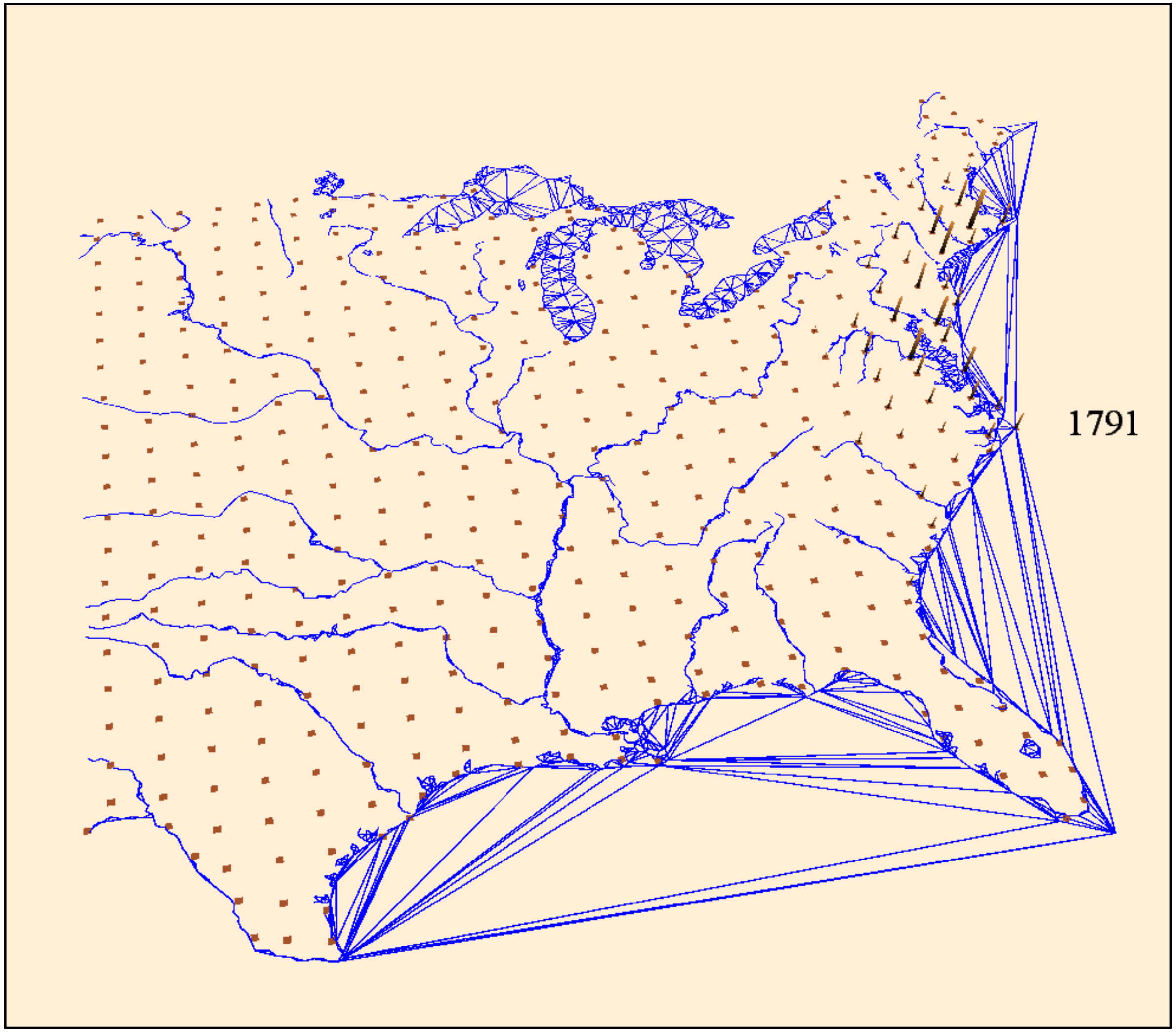
• ***Performance evaluation:*** *k*ernel density based two-sample comparison test for multi-dimensional data originally developed in biology to examine cell morphology after a given manipulation (Duong et. al. 2012).

Example 6. Venturing into history and archeology

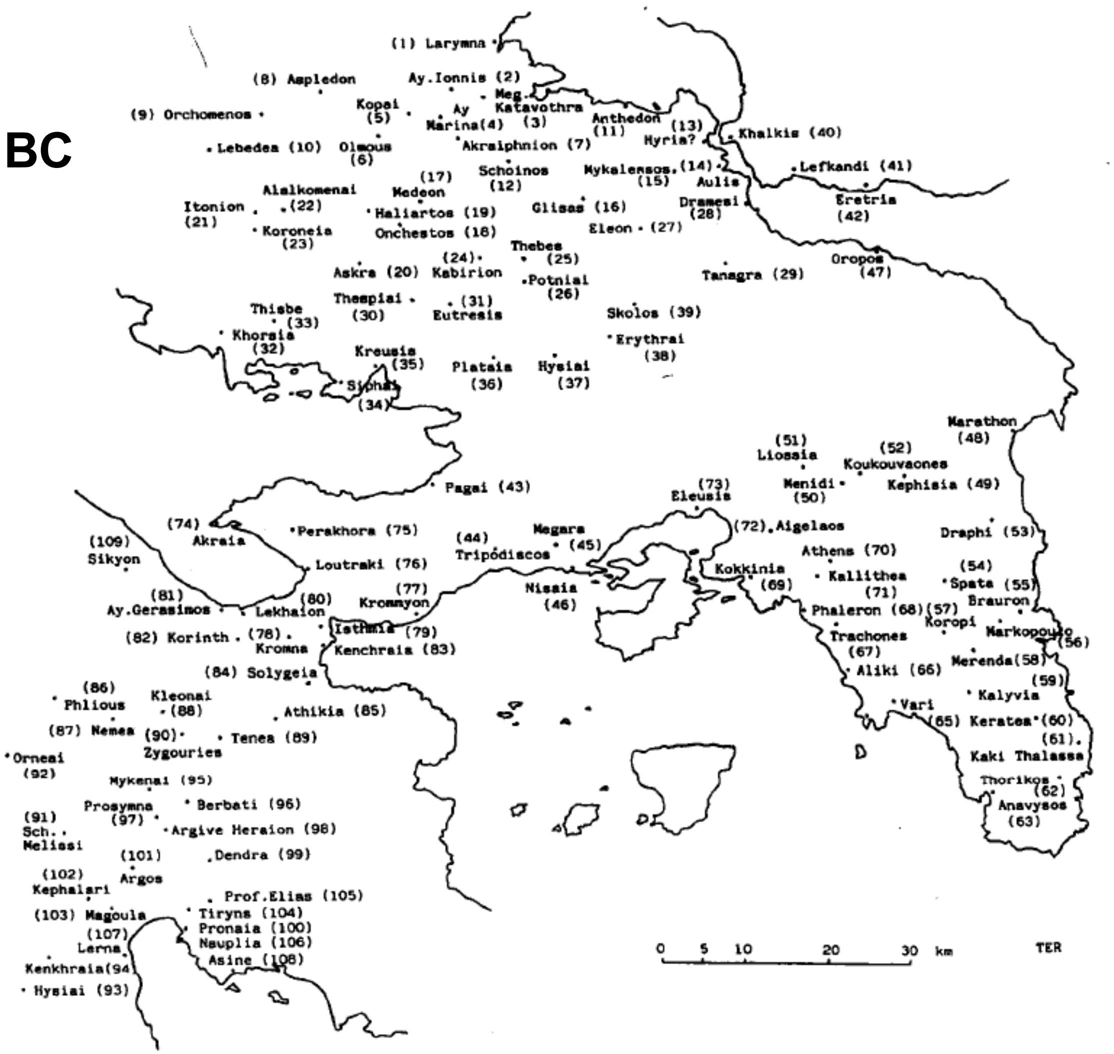
- the evolution of Chicago
- settlement structures in ancient Greece
- and Iraq
- the progression of the Emperor’s army: Assyria

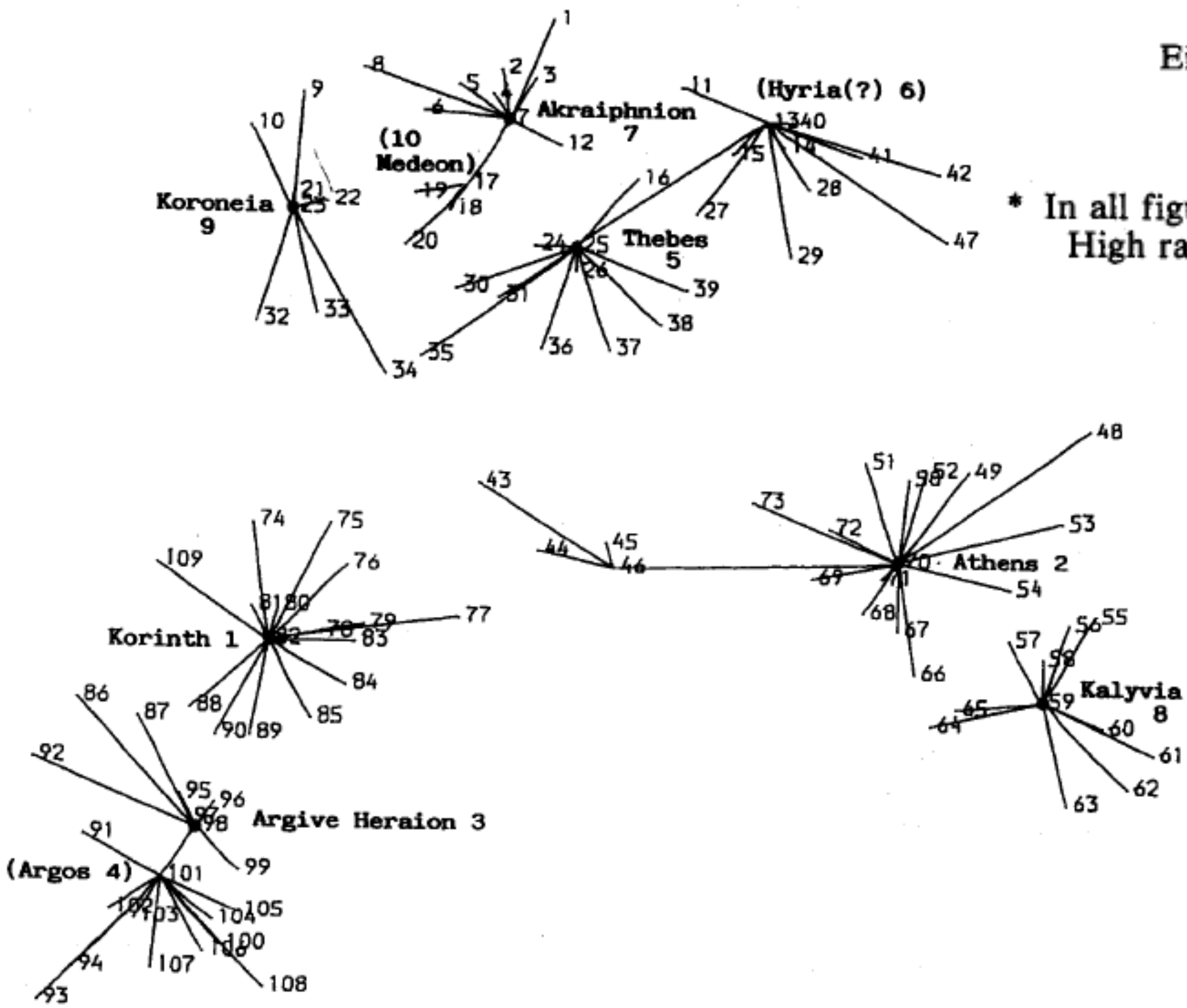
6.1. Chicago: model area and period

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


1791

6.2. Greece
9th Century BC





Eight systems (with topographical weightings).

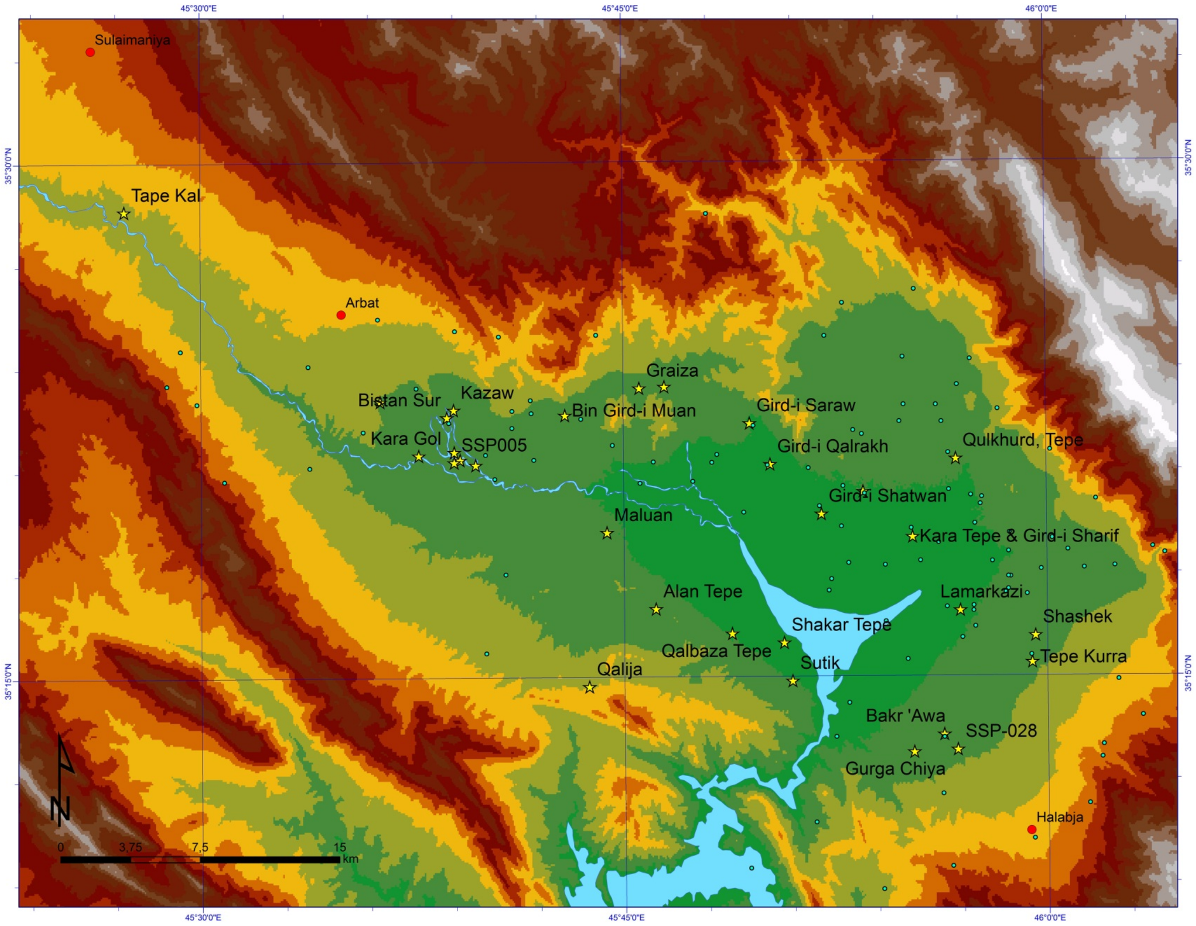
$\alpha = 1.01$

$\beta = 0.15$

Maximum flows only depicted.

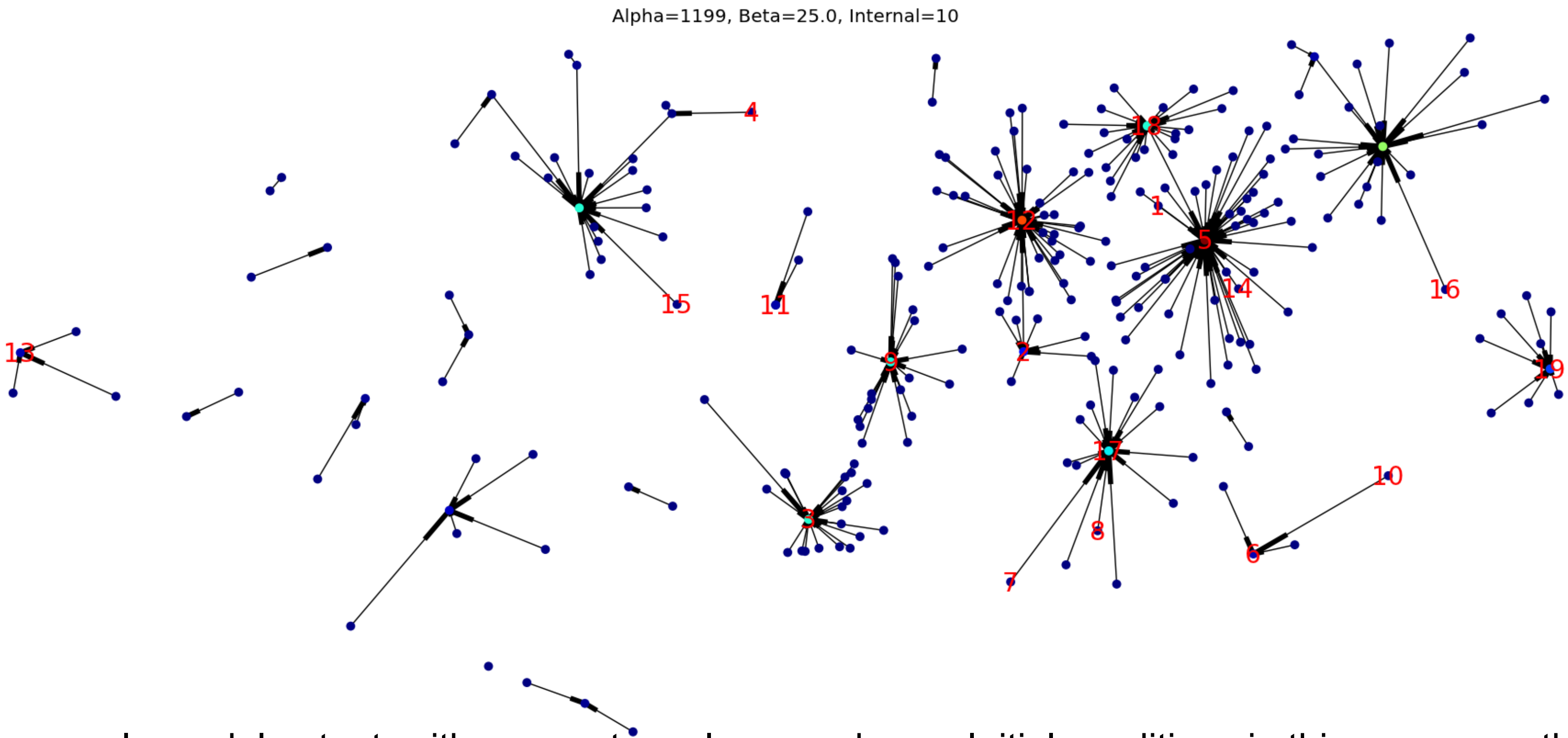
* In all figures the number is the predicted rank of a named site.
High ranking but non-terminal sites are given in brackets.

6.3. Kurdistan: Shahrizor and Jazira



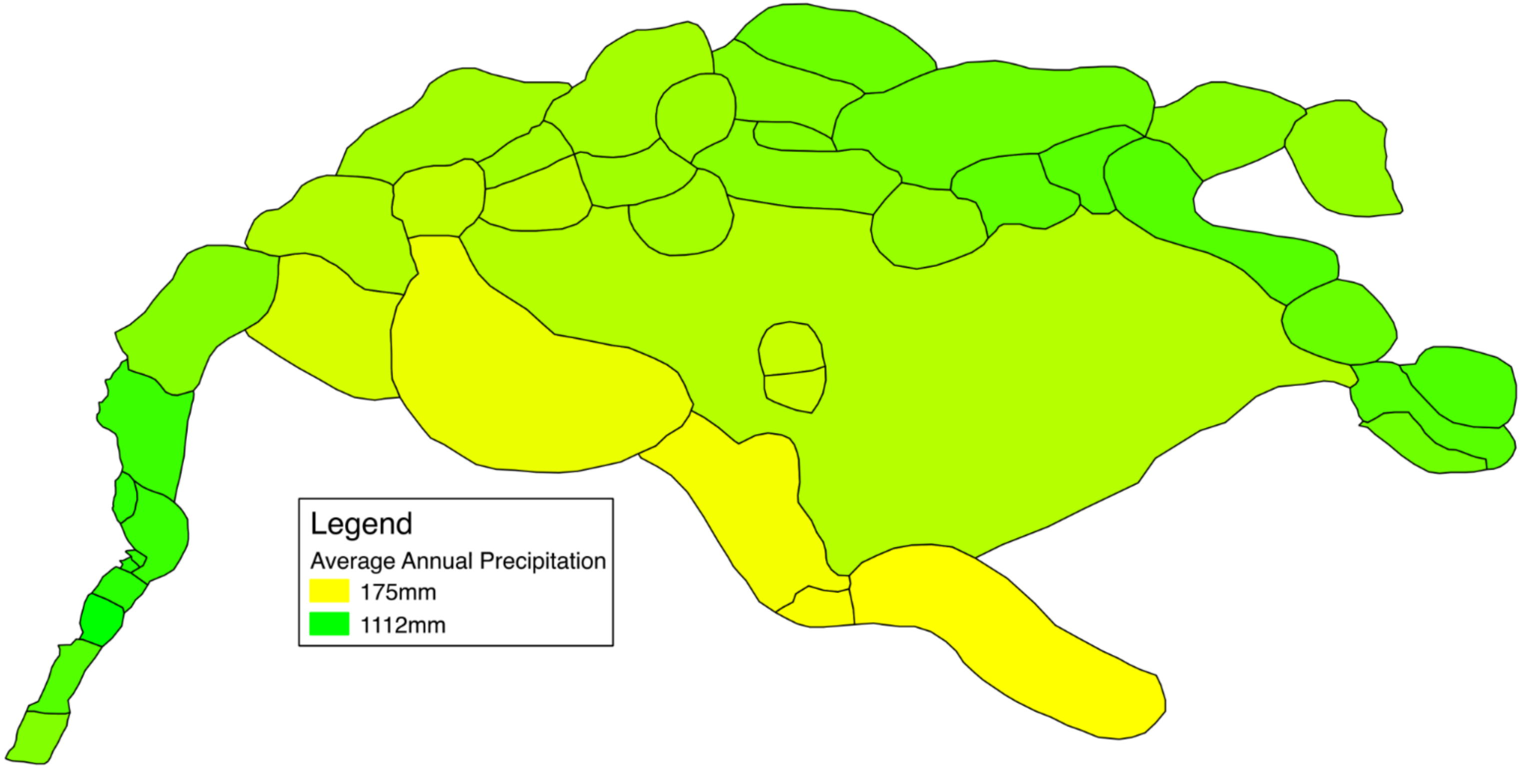
- Now part of Iraqi Kurdistan.
- Satellite imagery shows 111 sites, 30 of which have been visited.
- Can spatial analysis techniques (such as those seen in the retail model) predict which sites were likely to be centres, and hence of archeological importance?

Jazira region: Middle Bronze age



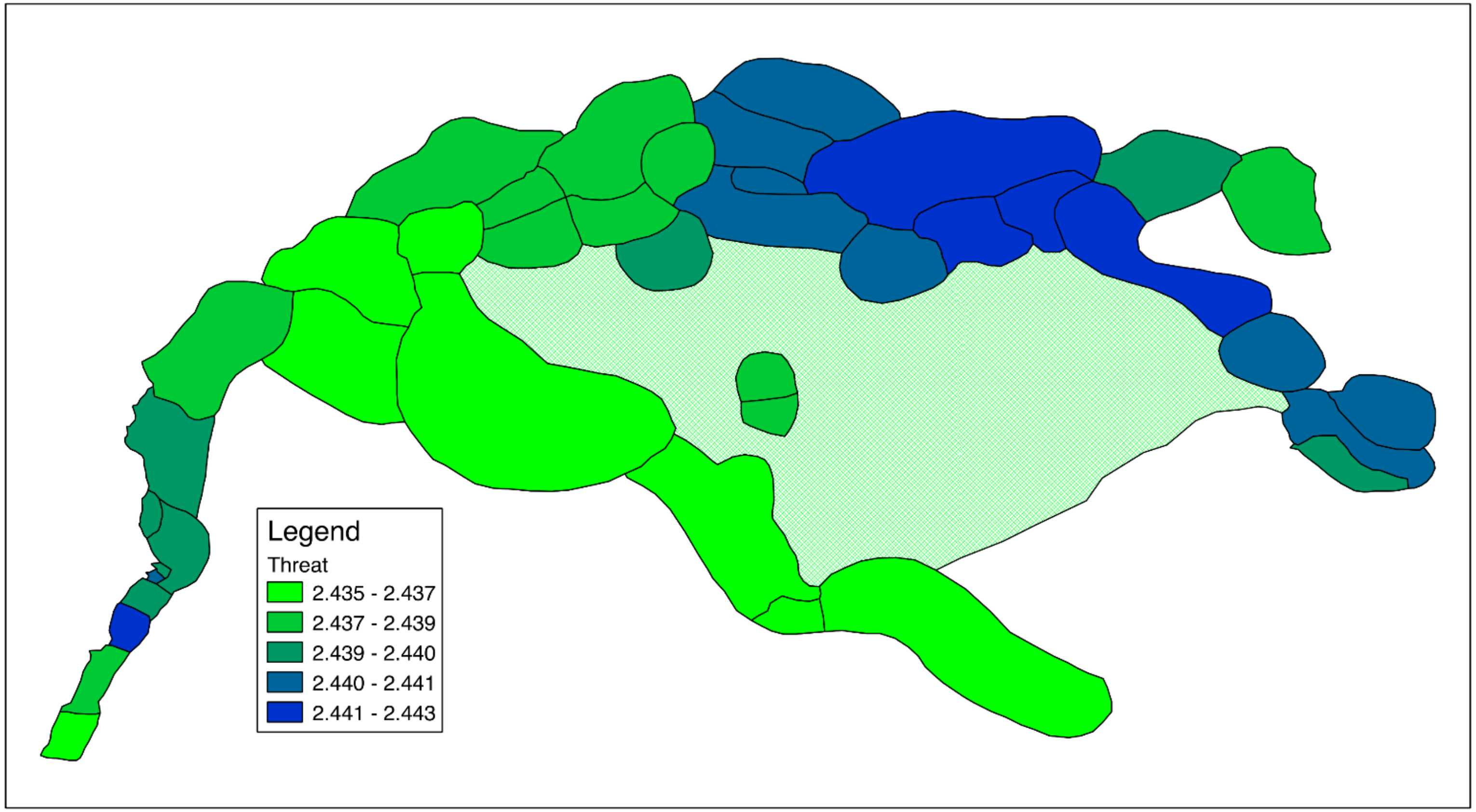
One example model output, with parameter values as shown. Initial conditions in this case were the ‘small/medium/large’ classification on the basis of real data. Arrows represent the derived Nystuen-Dacey network.

6.4. Expansion of the Neo-Assyrian Empire 883-859BC



- During this time period, the Neo-Assyrian Empire underwent large expansion due to large-scale, strategic and often brutal military campaigns.
- Our aim was to understand what made an area attractive to the Empire by considering static factors, such as the level of precipitation.

Expansion of the Neo-Assyrian Empire 883-859BC



- Outstanding research questions include determining the optimal distribution of Assyrian forces, so that the maximum level of threat is projected across as wide an area as possible.
- Understanding such questions could have helped the Assyrians defend their empire from rebellion, for example

5. A bigger challenge: dynamics

- cities and regions as complex adaptive systems:
  - multiple equilibria
  - phase changes
  - path dependence (importance of initial conditions)
- L-V approach offers real insight
  - 40th anniversary of Harris and Wilson (1978) but under-developed

5.1. The Harris and Wilson dynamic retail model

- the H-W model is usually presented as

$$dQ_j/dt = [a - a_{11}Q_j]Q_j$$

but can be

$$dQ_j/dt = [a - a_{11}Q_j]$$

5.2. Tha Bass marketing model

- I recently discovered by accident the paper by Bass (1969) that combines these two elements:

- $$dQ/dt = \alpha[a - a_{11}Q] + \beta[a - a_{11}Q]Q$$

- in his model, dQ/dt is the rate of take up of a new product; the first term on the rhs is interpreted as the take up by 'adopters' and the second by 'imitators' – weighted by α and β respectively

5.3. A general model

- we now introduce a model with N ‘species’, n = 1, 2, …….N and space through zones i = 1, 2, ……I, say.

$$dQ_j^n/dt = \gamma_j^n[H_j^n(Q_i^m, u_i^m) – \Sigma_{im}a_{ij}^{mn}Q_i^m]$$

$$+ \varepsilon_j^n[H_j^n(Q_i^m, u_i^m) – \Sigma_{im}b_{ij}^{mn}Q_i^m]Q_j^n$$

5.4. An even more general model: adding Turing diffusion

$$dQ_j^n/dt = \gamma_j^n[H_j^n(Q_i^m, u_i^m) - \Sigma_{im}a_{ij}^{mn}Q_i^m]$$

$$+ \varepsilon_j^n[H_j^n(Q_i^m, u_i^m) - \Sigma_{im}b_{ij}^{mn}Q_i^m]Q_j^n$$

$$+ d_j^n\partial^2 Q_{jn}/\partial x^2$$

5.5. Combinations: eight cases

$\gamma \neq 0$, $\varepsilon = 0$, $d = 0$ (Richardson, Harris-Wilson-1)
$\gamma = 0$, $\varepsilon \neq 0$, $d = 0$ (Lotka-Volterra, H-W-2)
$\gamma \neq 0$, $\varepsilon \neq 0$, $d = 0$ (Bass)
$d \neq 0$ some a and b non-zero (reaction-diffusion)
$\gamma \neq 0$, $\varepsilon \neq 0$, $d \neq 0$ (all processes operating)

the first three can be ‘with space’ or ‘without’, hence eight cases

5.6. Adding dynamics to the Lowry model

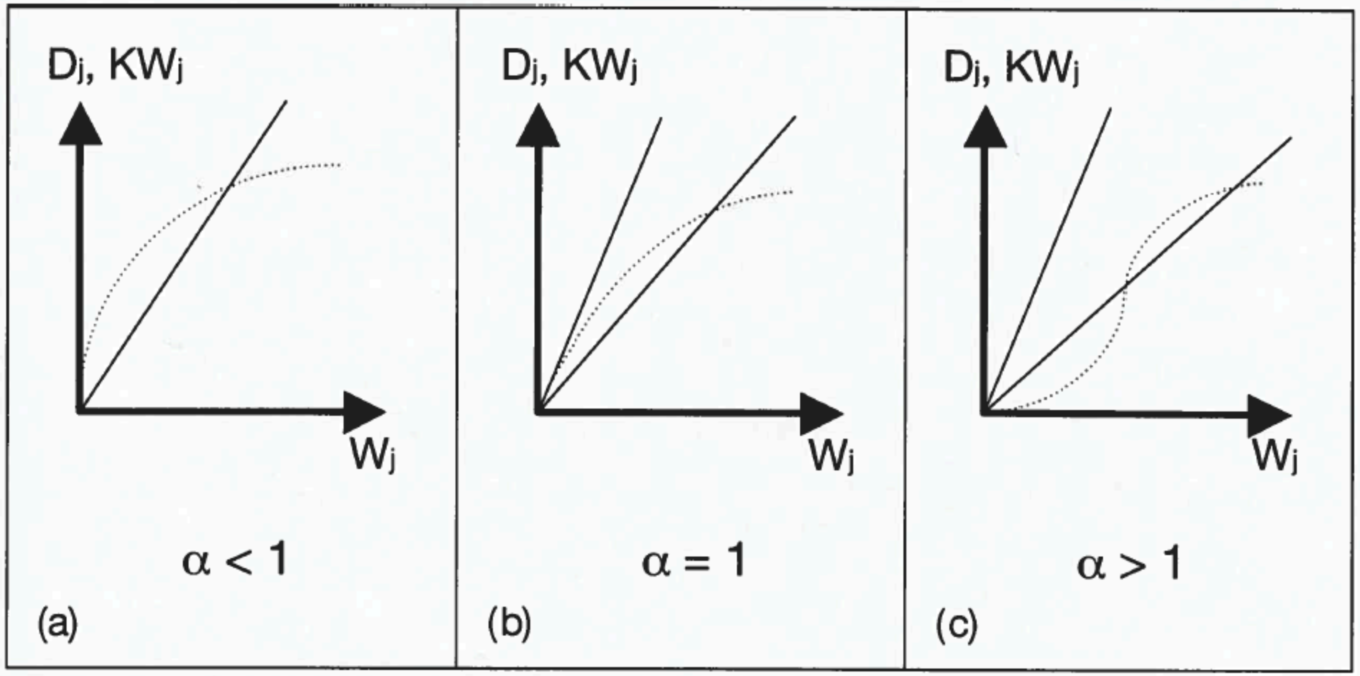


Figure 1.2 Revenue-cost curves for varying α

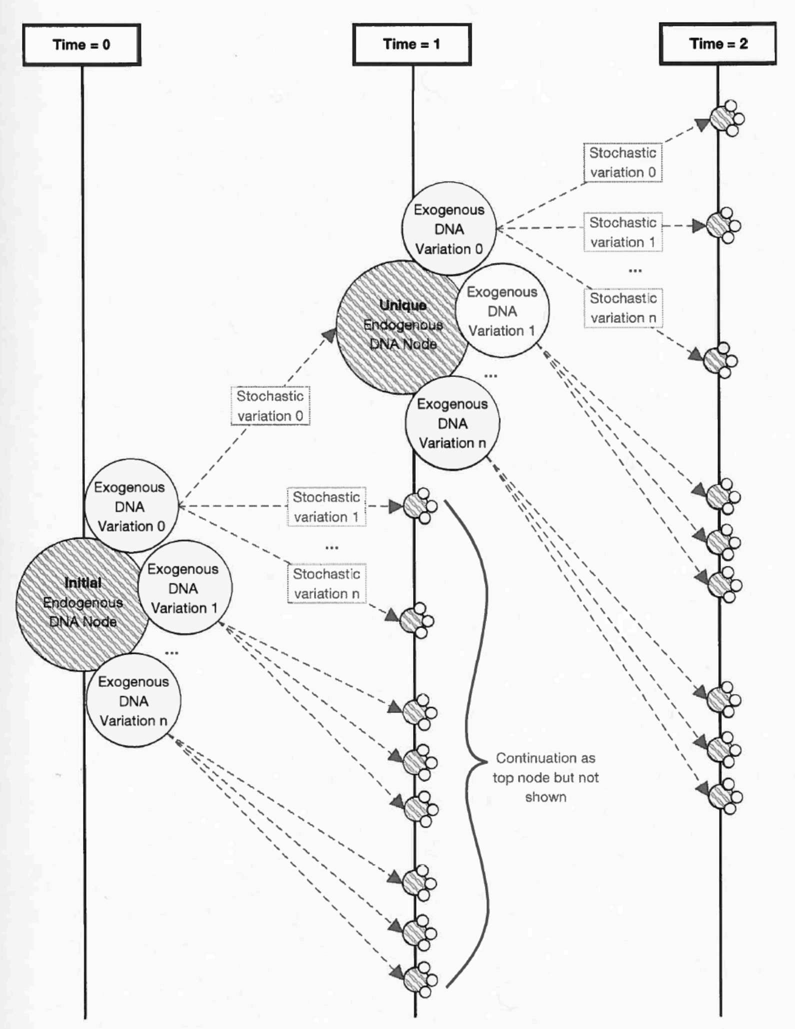


Figure 3.1 The tree structure inside the possibility cone of development

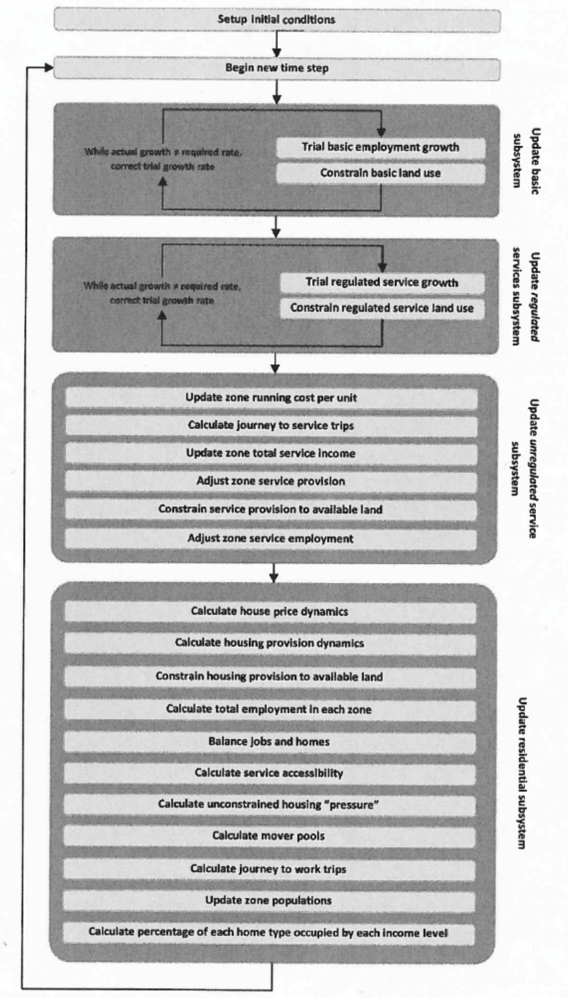


Figure 4.1 Time-step flow diagram

6. Integration

- finishing off the ‘theory’: integrating across paradigms
- scales
- concepts across disciplines
  - generalised cost, generalised utilities – an integrating factor via probabilities and ‘rules’
- conditional probabilities
  - across scales – ABM etc – D and W example
  - Bayesian underpinnings
  - causation
    - graphs
    - iterations

7. New mathematics, new algorithms

- structural dynamics
- machine learning
  - pseudo data – house prices as an example
- topology
- high dimensional spaces
  - ML on dynamic model outputs in hi-dim spaces

7.1. A breakthrough? Interaction model calibration from the structure

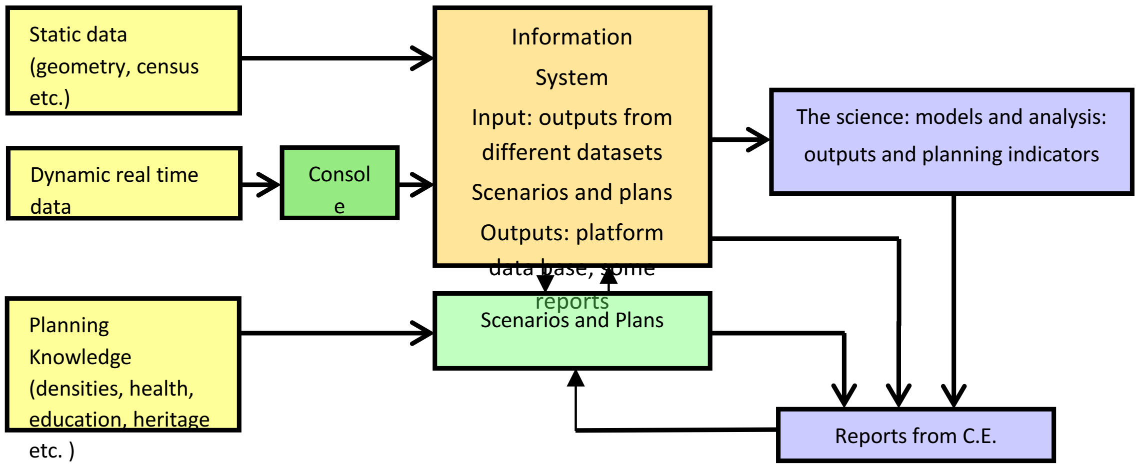
(1) $dX = -\nabla V(X)dt + \sqrt{2\gamma^{-1}}dB,\ X(0) = x \qquad X = \{Wj\}$

(2) $-\left(\nabla V(x)\right)_j = \epsilon \Pi_j(x) = D_j(W) - \kappa W_j, \qquad j = 1, \dots, M$

(3) $\epsilon^{-1} V(x) = \underbrace{-\sum_{i=1}^{N} \alpha^{-1} O_i \ln \sum_{j=1}^{M} \exp\left(\alpha x_j - \beta c_{ij}\right)}_{Utility} + \underbrace{\kappa \sum_{j=1}^{M} w_j\left(x_j\right)}_{Cost} - \underbrace{\sum_{j=1}^{M} \delta_j x_j}_{Additional} \qquad w_j\left(x_j\right) = \exp x_j, \qquad j = 1, \dots, M$

(4) $dW_j = \epsilon W_j \left(D_j(W) - \kappa W_j + \delta_j + \frac{\sigma^2}{2}\right) dt + \sigma W_j dB_j, \qquad j = 1, \dots, M$

8.. Integrating with planning: an analysis machine



Roumpani, Hudson-Smith and Wilson, 2014

9. Summary: priorities

- data/information system
- extending the range
- incorporating dynamics and using the insights
- integrating across 'paradigms'
- new mathematics and algorithms
- effective application

References-1: books

- *Knowledge power* (Routledge, 2010),
- *The science of cities and regions* (Springer, 2012)
- *Urban modelling* (5 vols, edited, Routledge, 2013)
- *Explorations in urban and regional dynamics* (with Joel Dearden, Routledge, 2015)
- *Global dynamics* (edited, John Wiley, 2016)
- *Geo-mathematical modelling* (edited, John Wiley, 2016)
- *Collaborative approach to trade: enhancing connectivity in sea- and land-locked countries* (with Francesca Medda et al, Springer, 2017)

References-3: papers

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References-2: Foresight – Fututre of Cities Reports ………..

Overview of the Evidence:
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/520963/GS-16-6-future-of-cities-an-overview-of-the-evidence.pdf

Science of Cities:
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/516407/gs-16-6-future-cities-science-of-cities.pdf

Foresight for Cities:
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/516443/gs-16-5-future-cities-foresight-for-cities.pdf

Graduate Mobility:
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/510421/gs-16-4-future-of-cities-graduate-mobility.pdf