Simulation In Innovation: What models of innovation generation, diffusion and impact can teach us

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The book

- This paper draws upon the book

- See the website to download models
  http://www.simian.ac.uk/resources/models/simulating-innovation

- What’s it about?
  - A critical survey of simulation models in innovation studies: (1) complexity science, (2) diffusion models, (3) social networks, path dependence, herds and fads, (4) organisational learning, (5) scientific publication, (6) ANT & SCOT, adopting & adapting, innovation as constraint satisfaction, (7) technological evolution, innovation networks
Today’s contents

• Why simulate innovation (using ABMs)?
  – Explain stylised facts and patterns in terms of micro-level generative mechanisms

• How not to simulate innovation
  – It’s not about forecasting single numbers
  – It’s not about the diffusion of some new thing

• Some examples (3 today)
  – Collective learning model, Percolation model, Hypercycles model

• Key themes
  – Collective intelligence as heuristic search, Representation of innovation, Input structures, Output structures, Networks as inputs and outputs
WHY SIMULATE INNOVATION?
Tools for thinking

• Models are *tools for thinking*
• They focus our attention on particular things
  – Phenomena they will explain
  – Causal mechanisms which they represent
• They may divert attention from other things
  – E.g. Pre-crisis economics
    • Mainstream, neo-classical economics focuses on market equilibria
      – Crises and crashes are not supposed to happen
    • Humans and organisations are assumed to be “rational agents”
      – Selfish optimisers, with perfect information and instantaneous ability to choose
    • Analysis is easiest if every agent is identical
      – So ignore inequality
Tools for rethinking economics

• **We need better tools for economics**
  – Psychologically realistic decision making
  – Agents motivated by more than money
    • Input from psychology, sociology, cognitive science
  – Heterogeneous agents
  – Role of social networks, not free markets
  – Non-linear inputs
  – Non-equilibrium outcomes
  – Etc.

• **Tools for evolutionary economics**
  – And neo-keynesian, behavioural, marxist…
Agent-based simulation models as the tool?

- What ABMs offer
  - Heterogeneous agents
  - In social networks of interdependencies
  - Random variation in behaviour
  - Adapting to dynamic (co-adapting) environments
  - Bounded (rational?), heuristic decision making using limited information
  - Generate emergent phenomena
Modelling for Business Analysts

1. Get historical, quantitative data
   - Effort: How many calls the sales reps made in each area
   - Response: How many sales were obtained in each area

2. Get mathematical model
   - Making a few theoretical assumptions

3. Fit model to data

4. Interpret model for client
   - “If X is your effort, you will get $Y in response.”
   - “X will cost you Z.”

5. Make recommendations
   - “Choose X = 2 to maximise profit.”

6. Boost client’s sales(?), justify your fee, …
Simulation models in Operations Research

• “Simulation” in O.R. means discrete-event simulation
• Typically used for representing queueing systems
  – Customers waiting for service in supermarket, post office
  – Patients waiting for operation
  – Cars waiting for traffic lights
• How many servers do I need?
  – Waiting bad for customers, therefore bad for business
  – Servers cost money
• How should I structure my queues?
  – 1 queue for n servers, or n queues for n servers?
Pattern-oriented modelling

- In *Social Simulation* we rarely make quantitative forecasts.
- Rather we connect **social mechanisms** to the **patterns** that emerge from them.
  - Qualitative outcomes, not forecasts of single numbers.
  - We link micro to macro.
    - But without the hard maths. and the dodgy behavioural assumptions.
- We provide **plausible** explanations.
  - Not **probable** ones.
    - Unlike statistical modelling.
  - Not **deterministic** ones.
    - Unlike mathematical deduction.
  - Not **necessary** ones.
    - Unlike Kantian philosophy.
Why simulate innovation?

• **Bridge the micro-macro gap**
  – There are various stylised facts concerning innovation
  – Models of micro-level social mechanisms may be able to generate these macro-level facts
    • Pattern-oriented modelling

• **Demonstrate a sufficient cause for the pattern**
  – Although alternative explanations may exist

• **Demonstrate when emergence is and is not likely to occur**
  – Network structures, behavioural practices, environmental dynamics
Why not other research methods?

• **Complexity**
  – Heterogeneous agents with multiple mechanisms may have non-trivial, emergent phenomena, e.g. autocatalysis
  – Hard for quantitative and mathematical approaches to reproduce this

• **Experimentation**
  – Practical, ethical reasons prevent experimentation and answering what-if hypotheticals
  – Qualitative studies struggle to obtain the scale needed to explain macro-level patterns
What do we mean by innovation?

• Ideas, practices, beliefs, technologies, processes, roles, structures, organisations… that are
  – **New**, novel, newly invented, created, emerged or introduced
  – **Useful**, valuable, practical, having an important effect

• **Most of the models are highly abstract!**
  – Though their authors may have had particular case studies in mind, and even (occasionally) some empirical data
    • E.g. the SKIN model
HOW NOT TO SIMULATE INNOVATION?
The linear model of innovation

• Three distinct phases identified
  – **Innovation**, **Invention** or **Introduction** of innovative thing, product, practice, technology, etc.
  – **Diffusion** of the innovation
  – **Impact** of the diffusion
    • On adopters, inventors, suppliers, other technologies and services
Critique of the linear model of innovation

• Should we separate the phases?
  – The origins or generation of innovation is often left a mystery
  – Once launched, an innovative product may be reinterpreted, reapplied, modified by its users
    • “To adopt is to adapt” (Akrich et al.)
    • The innovation is not fixed over time, nor identical to all potential adopters
  – Innovations’ impact may include affecting the chances of their further adaptation and diffusion, and the generation of new innovations
    • E.g. Our desire for compatibility in information technology leads to positive feedback loops, increasing returns to scale, market lock-in on inferior designs
Webs of technologies & practices

• Innovative technologies do not diffuse in a vacuum; they have competing, dependent and supporting products and services

• Creative destruction:
  – New technologies can destroy whole webs of interdependent technologies, practices & roles, while enabling new webs to form
    • The automobile rendered obsolete the horse, the cart, the haymaker, the blacksmith, etc.
    • The automobile needed petrol stations, tarmac roads, mechanics, etc.
    • The automobile made possible roadtrips, drive-in cinemas, out-of-town shopping malls, mega-churches, etc.
The diffusion curve

- Ryan & Gross (1943) data on adoption of hybrid seed corn among Mid-west farmers
  - Total adoption to date followed an S-curve
  - Adoption rate rose to a peak then declined
- Focus on
  - Take-off point
  - Point of peak rate
  - Market saturation level
Rival models for the diffusion of innovations

- **Epidemic model**
  - Innovations spread like an infectious disease
    - Word-of-mouth advertising
    - Imitating the neighbours
  - Preferred explanation for sociologists
  - Focus on
    - structure of social networks
    - who are the hubs in the net
    - charismatic super-persuaders
    - communication practices

- **Probit model**
  - Heterogeneous agents repeatedly reconsider decision to adopt in changing environment
  - Preferred explanation for economists
  - Focus on
    - Decision makers’ attributes
      - Size, wealth, knowledge, capabilities
    - Changing socio-economic context
      - Market price, economic confidence, public experience of the innovation
The two explanations can be incompatible

- Rogers (1958) categorised adopters by when they adopted:
  - innovators; early adopters; early majority; late majority; laggards
- Rogers (2003, ch.7) identified relations between these categories and socio-economic and personality attributes of adopters
- The simplest epidemic model (the S-I model) is not compatible with this diversity in adopter attributes
  - Either adopter attributes will give too little information about future adoption to be useful
  - Or the adoption rate curve will be skewed, not symmetrical
  - The adoption rate curve (from the logistic function) has a different shape from a normal distribution for attributes
    - They have different mathematics

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Forecasting adoption will rarely be useful

- Models that omit random variation will produce expensive errors

- Models fit to time-series data will
  - either have too little data and make expensive mistakes about how many will eventually adopt
  - or require too much data and provide accurate forecasts too late to be of use
    - The peak adoption will have already occurred

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Rethinking innovation: it’s complex

• More focus on networks of interdependencies among diverse parts
• More focus on generation, adaptation and reinterpretation of innovations
• More focus on dynamic context of adoption
• More focus on chance events leading to later lock-in
  – Less focus on the attributes of the winners
Diffusion in a social network

• If individuals are influenced in adoption by their friends, neighbours and colleagues, network structures become important

• Who is the best person to start diffusion?
  – Target the hub, the one with shortest paths to others or the bridge between groups?
  – This varies with network structure
Competing diffusions

- How does network structure affect the outcome of competing diffusions?
  - E.g. the relative numbers of adopters of two technologies, “Blue” and “Green”
- Path dependency: Early adoption decisions affect the chances of later adoption decisions
- Network structure affects the distribution of possible outcomes:
  - 0% Blue:100% Green, 10%:90%, 50%:50% etc.
  - In random networks, all outcomes are equally likely
  - In regular networks, a 50:50 balance is the most likely
    - the fairest network?
  - In tree structures, winner often takes all
Social learning

• If adopters have only weak ability to judge the value of adopting, can they improve this by imitating others?

• **Information cascades**: after the first few adoption decisions, a cascade of copycat adoptions occurs
  – Herd behaviour

• Rational agents should factor this in: agents adopting as a herd do not provide extra information about the innovation

• But decisions that surprisingly buck the trend may reflect new information
  – Mavericks who ignore the trend can benefit the collective

• Network structures affect how often we need to learn from others and how often make our own judgment
SOME SIMULATION MODELS
Simulation models of innovation


- More references available in the book

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Questions for comparing models

• What is the innovation?
  – e.g. new idea, belief, combination, theory, product, process, sequence, organisation, structure…

• How is it represented in the model?
  – Bit string, Transformation rule, Vector position in state space, Network of agents…

• What input structures are assumed?
  – Social networks, Fitness landscapes, Environment, Desired functions…

• What patterns emerge?
  – Growth curves, Frequency distributions, Networks…
Three types of example

1. Models of organisational learning
   – Innovation as collective problem solving

2. Models of technological evolution
   – Innovation among interdependent technologies

3. Models of emergent, novel organisation
   – Emergent networks and other structures from individual actors’ activities
Type 1: Explore & exploit: Models of organisational learning

- Individuals in a firm seek new, better combinations of routine practices
  - “Better” is assumed to be common to all; every employee is motivated by the same objective or goal
- They use heuristics, routine innovation practices, to search for these combinations:
  - Trial-and-error experimentation
  - Learning from others
- Aim for a balance between exploration of new combinations and exploitation of ones already found
- If sharing ideas, avoid groupthink and premature convergence on inferior solutions
Lazer & Friedman’s model of collective learning

- **Object:** bit string representing combination of binary beliefs
  - Knowledge increases through agents’ use of trial-and-error and learning-from-others heuristics
- **Input structures:**
  - Fitness landscape (Kauffman’s NK)
  - Social network for agents
- **Output structure:** Fitness improvement curve
- **Problems solving performance varies with**
  - Relative frequency of different innovation practices
  - Social network structure among problem solvers
Refocusing organisational learning

• Most models assume individuals seek solutions to the same problem
  – The firm’s goal, e.g. the firm’s profits
• Most models investigate what produces the best expected, or average, fitness
  – But individuals are often rewarded for their individual successes
  – If winner takes all, it may be more rational to take risks, adopt innovation practices with more variance in success
• Given fixed resources and gambles with negative expected payoffs, individual survival may be longer if you prefer high-risk, high-payoff activities
Type 2: Models of technological evolution

- Innovations make possible further innovations
- Innovations render previous ones obsolete
- The size, or importance, of an innovation may be defined in terms of its effect on other innovations

- What is the distribution of changes?
  - Periods of small, incremental changes, punctuated with brief periods of revolution
  - Scale-free: changes occur on all scales
- It becomes hard to forecast which will be the most important innovations, and who will be their inventors
Silverberg & Verspagen’s Percolation model of technological evolution

• Object: technologies in technology space are nodes in grid; R&D leads to percolation
  – Highest node is state of the art
  – Innovations are jumps in state of the art
• Input structure: grid structure
• Output structure: scale-free frequency distribution of innovation sizes
Arthur & Polak’s model of technological evolution

• **Object**: logic circuit composed of NAND gates
  – **Knowledge**: set of circuit designs, each composed of other members

• **Input structure**: evaluate using list of desired logic functions
  – New designs may replace older ones because satisfy more functions or cheaper/simpler
  – **Innovation size**: the number of technological designs rendered obsolete and replaced

• **Output structure**: scale-free frequency distribution of technology replacement sizes
Type 3: The emergence of novel organisation

- Not innovation as new combinations of things, but the emergence of new things
- New products are part of webs of supporting practices and technologies
- Under what circumstances can new network structures emerge without complicated processes of design?
  - Self-organising: individual actors create the structure through their activities
- What structural properties will the emergent networks have?
  - Self-maintaining: the structure determines the continued success of particular roles for the actors
Padgett’s hypercycles model of economic production

- **Object:** production rules (Given a “0”, turn it into a “1”)
  - Knowledge: firms increase their stocks of rules through learning-by-doing

- **Input structure:** heterogeneous firms organised in a social network
  - Firms transfer their output products to neighbours to use

- **Output structure:** self-organised, self-maintaining network of firms with rules
  - A novel object
  - Think about the emergence of organisations and markets, life, etc.
CJZ’s model of emergent innovation networks
(Cowan, Jonnard & Zimmermann 2007)

- **Object:** quantities of knowledge represented in several dimensions
  - Collaboration produces increases in quantities
    - Cobb-Douglas production function
- **Input structure:** none specified
- **Output structure:** social networks
SKIN model (Ahrweiler, Gilbert, Pyka, Simulating Knowledge dynamics in Innovation Networks)

• Objects: vectors (kenes) used for producing other vectors; recipe (innovation hypothesis) for doing this
  – Knowledge: firms fund R&D, trade expertise on market, form alliances (innovation networks)

• Input structures?
  – kenes are just maths
  – Firms could have network structure

• Outputs: scale-free distribution in innovation network size
WHAT WE LEARNT
There are a lot more models than this!

- If I had a euro for every paper containing a diffusion model…

- The book might not cover your favourite models in innovation studies
  - So ask: What, if anything, would other models add to the features in the paper’s or book’s models?

- How would you apply a model to a real case or pattern?
Key themes

• **Innovation is the product of collective effort**
  – Human agents can solve problems collectively using simple routine search practices, that as individuals they would be unlikely to solve on their own
  – Some organisational structures and practices are better than others for generating innovation

• **Innovation is usually recombination of existing parts**
  – Innovation can be reinterpretation of existing technology
    • Tracing new trajectories in technology space
    • Exaptive bootstrapping (Villani et al.)

• **New objects can emerge as self-maintaining / auto-catalytic structures**
Problem: Combining mechanisms

- Real human agents belong to multiple networks at any one time and engage in multiple practices
- Combining micro-level mechanisms might mean they no longer generate the desired patterns
  - Our model of academic publication produced realistic growth curves and frequency distributions
  - Then we added the concept of authors engaging in heuristic search for better combinations of ideas
    - As seen in models of organisational learning
  - Suddenly it became much harder to calibrate a model!
## Model replication is possible

<table>
<thead>
<tr>
<th>Model</th>
<th>Attempted?</th>
<th>Did it work?</th>
<th>Causes</th>
</tr>
</thead>
<tbody>
<tr>
<td>L&amp;F’s Learning</td>
<td>Yes</td>
<td>Perfect</td>
<td>Easy model, Uses NK fitness, Good variance reduction</td>
</tr>
<tr>
<td>S&amp;V’s Percolation</td>
<td>Yes</td>
<td>Nearly perfect</td>
<td>Easy model / clear description</td>
</tr>
<tr>
<td>Padgett’s hypercycles</td>
<td>Yes</td>
<td>Nearly perfect</td>
<td>Multiple papers</td>
</tr>
<tr>
<td>A&amp;P’s Tech. Evolution</td>
<td>No</td>
<td>-</td>
<td>Big computer X lots of time</td>
</tr>
<tr>
<td>CJZ’s innovation networks</td>
<td>Yes</td>
<td>No!</td>
<td>They “deleted” their original code</td>
</tr>
</tbody>
</table>
Download models from the website

- Our own models
- Our replications of classic models

[www.simian.ac.uk](www.simian.ac.uk)

- And don’t forget to look out for the book!

STYLISED FACTS
ABOUT INNOVATION
Stylised facts

• Patterns found in quantitative data
  – Academic publication data
  – Social and firm network structures
  – Technological change

• These are regularities that social science needs to explain

• Which methods can do it?
Innovation is progressive, as learning or problem solving

- While searching for what goes well with what, ever better solutions to problems are found over time
- Older solutions are rendered obsolete and replaced

- Diminishing returns to search effort?
  - As you approach the optimal or peak solution
Quantitative innovation & trajectories

• Many technologies display quantitative improvements over time in quality
  – Better, faster, cheaper
  – At a constant rate, e.g. Moore’s law

• Even when there are changes in component technologies or innovators
  – Vacuum tubes, transistors, silicon chips
  – France, Britain, USSR, USA

• Trajectories in technology space?
Air speed records

Computing cost

Innovation in the innovation rate

  - Quality-doubling times for various technologies, different choices of quality
  - What happened around 1840?
Qualitative innovation: new things and structures emerge

• The number of goods available increases over time

• Beinhocker, 2007, pp. 456-457:
  – A human being 10000 years ago had 100s of goods available
  – In a US city today there are $10^{10}$ barcodes for things

• Explain in terms of *exaptive bootstrapping* (Villani et al. 2007)?
Scale-free distribution in “innovation size”

- Financial value: Innovators make money (sometimes)
- Use: Innovations are components for later innovations
- Use / Attention: Innovations are cited
  - Citation frequency distributions
- Effect: Innovations cause disruptions, obsolescence, bankruptcies
  - Schumpeter’s “perennial gale of creative destruction”
Distinct types of innovation?

• Incremental and radical…
• …and architectural and modular
Social network structure

• Networks of
  – people, firms, regions, etc.
  – academics, papers, topics,…
  – patents, authors, holders, institutions, places, …

• Produce SNA metrics, science maps

• Incorporate dynamics, endogeneity
  – Networks produce and are produced by innovations
  – Coadaptation