Modelling Energy Technology Diffusion on Networks

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Introduction

Focus of the Case-Study

Complex Network Models

Dynamical Models

Model Results

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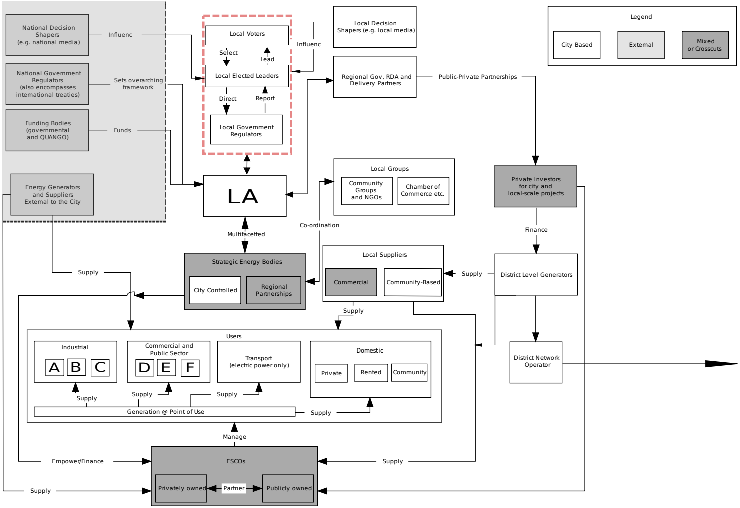
Introduction

Can complexity science contribute to city energy policy?



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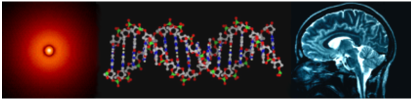
What is "Complexity Theory"?

1. Characteristics of a complex system:
    - Multiple interacting individuals,
    - interactions important to system level behaviour,
    - macroscopic *emergent* phenomena,
        - coherence & pattern,
        - "unexpected" outcomes.
    - *Universality*:
        - common behaviours in 'unrelated' systems,
        - identify basic underlying features.
2. Tools include ABM, networks, dynamical systems...

Measuring Complexity



Level of Complexity

Complex **System** or **Behaviour**?

Complex behaviour from simple rules ⟵ *Emergent behaviour* ⟶ **Order/Pattern from complexity**

Modelling the Real World

- Would like to predict specific outcomes of *interventions*.
- Not generally possible in chaotic and complex systems,
  - can give generic behaviours,
  - test whether system conforms to expectations.
- Models include only *essential features* of system.
- Can test *sensitivity* to model details and initial conditions.

Focus of the Case-Study

- Study interventions related to adoption of new technology or energy use strategies,
- mediated by social contacts between individuals (as well as through the media) [1].
- This dissemination of technology or ideas can be studied using models of diffusion on networks.

[1] e.g. see: R. Phillips and S. Rowley, *Bringing it home: Using behavioural insights to make green living policy work*, Green Alliance (2011).

Schemes Under Consideration

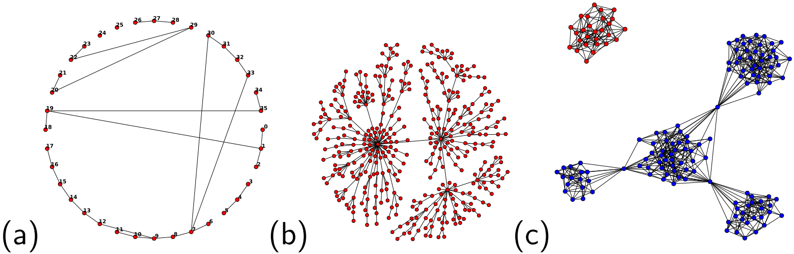
1. Green Deal provider covers upfront costs of EE tech, paid back from the savings in energy bills;
2. Subsidy for installing EE out of LA budget;
    - word-of-mouth about savings achieved,
    - incentives such as "recommend a friend discounts".
3. Smart meter installation;
    - effects of seeing own use compared to neighbours'.

Network Models

- Individuals, organisations, households, . . ., considered as *nodes* on a network.
    - Properties of nodes are associated with variables, e.g.:
        - ability to buy (income + subsidy),
        - willingness to buy (personal and social utility).
- *Links* (‘edges’) are drawn between connected individuals.
    - Information/influence passed along (weighted) edges.
- This is a *complex system* of interacting individuals.
- Dynamics of variables governed by equations (rules) based on own and neighbours’ state.

Types of Model Network

- Random networks constructed to a give different qualitative features of real world interactions:



(a): *Small world* network with 20% rewiring of a regular lattice.
(b): Preferential attachment graph with a *scale-free* degree distribution.
(c): Simple model of weakly-connected communities.

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Real-World Social Networks

- Different types of social connection exist; these include:
  - geographical neighbours, distant friendships, family trees, *communities*.

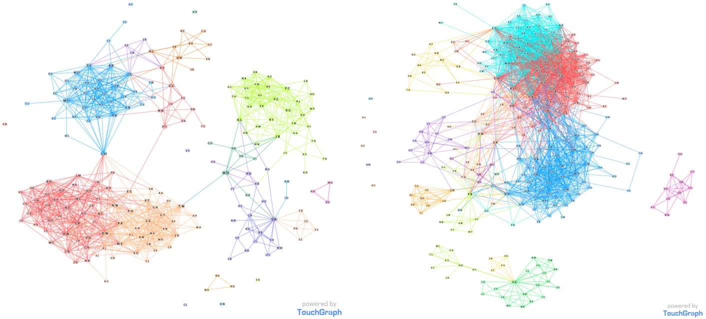

Figure: Inter-friend contacts on the *Facebook* website.

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Community-Structured Networks

- **Communities** are sets of individuals which are more well connected internally than to the rest of the network [2].
  - a distribution over a range of sizes exists,
- Most individuals will be connected to more than one group (work, leisure, children's school etc.).
- Varying degrees of overlap exist [3].
- This creates the cobweb of highly inter-connected groups.

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[2] S. Fortunato and C. Castellano, *Community structure in graphs* (2007).

[3] G. Palla, I. Derényi, I. Farkas, and T. Vicsek. *Uncovering the overlapping community structure of complex networks in nature and society* (2005).

Dynamical Models

Internal Dynamics could include the following factors:

- Rational cost-benefit analysis;
  - dynamical system on nodes,
  - defined decision criteria.
- Decisions based on influence crossing some threshold:
  - fixed number of friends or proportion of contacts.
- Could be probabilistic.
- Would likely have multiple parameters.

Social Dynamics and Diffusion Models

- Many models exist for social dynamics [4].
- We are more interested in technology adoption models:
  - Threshold models are often used:
    - individuals use the technology if a certain number or proportion of the neighbours are using it.
- Can quantify system "effectiveness" counting either:
  - number of individuals who have technology,
  - average opinion of technology.

[4] C. Castellano, S. Fortunato, and V. Loreto. *Statistical physics of social dynamics* (2009).

Models of Social Influences

Models weight individual's own preference relative to social influence [5]:

- *Utility* (benefit) of product to individual:

  $$U = \alpha p + (1 - \alpha) s$$

  p: personal utility: value of product to individual,

  s: social utility: fraction of other individuals with technology,

  α*:* relative weighting of personal to social value.

[5] S.A. Delre, W. Jager, T.H.A. Bijmolt, and M.A. Janssen. *Will it spread or not? The effects of social influences and network topology on innovation diffusion* (2010).

Personal Utility

Intrinsic to product and individual, could depend on:

- potential savings,
  - relative or absolute,
  - pay-back time;
- environmental credentials (may change),
- negative effects of barriers to adoption.

Social Utility

- Data suggests individuals assign different relative value to personal contacts and society [6].
  - someone buys when adoption within society and contact network are above respective thresholds,
  - individuals classed as early, majority or late adopters,

[6] T.W. Valente. *Social network thresholds in the diffusion of innovations* (1996).

Aspects to Include in Models

1. Use community-structured networks with wide degree-distribution,
2. Weight links of different types,
   - strength of influence of different individuals.
3. Use distributions of behaviour archetypes:
   - thresholds for personal and social utility, as well as prevelance in society in general (via media).
4. Market feedback effects such as *learning-curves*, whereby the unit price reduces with market penetration [7].

[7] S. Cantono and G. Silverberg. *A percolation model of eco-innovation diffusion: the relationship between diffusion, learning economies and subsidies.* (2009)

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Model Specifications

1. The individual households are nodes on the network.
2. Associated state variable $x_i = 0, 1$:

   0: not purchased, 1: purchased,

   - can also include continuous "opinion" region.
3. Weighted "value" of an EE product to individual is bundled into a *utility* variable, U_i
4. Threshold for adoption $\theta_i = C_i - I_i$,

   C: *perceived* "costs", I: incentives.

Model Specifications

5. At each time-step evaluate *utility* of product:

$$U_i = \alpha p_i + \beta s_i + \gamma m$$

$$s_i = \sum_j^{K_i} \rho_{ij} x_j / \sum_j^{K_i} \rho_{ij}, \; m = \sum_{k=1}^{N} \sigma_k x_k / \sum_k^{N} \sigma_k.$$

6. If $U_i \geq \theta_i$: $x_i \rightarrow 1$.

- Time-scales for updating opinion (τ_1) and making purchases (τ_2) may be different:
  - τ_1 opinion updated after interacting with friends and taking in media (e.g. weekly),
  - τ_2 purchase decisions made less frequently (motivated by monthly pay-day, weather, prices, breakages etc.).

Modelling Interventions

- Measure diffusion with and without a given intervention.
- Compare possible interventions, e.g.:

1. street-by street targeting for installation;
2. targeting communities and opinion leaders,
3. ‘random’ installation,
    - e.g. via advertising campaign;
4. ‘word-of-mouth’ propagated installation,
    - strengthening network ties to improve communication.
    - e.g. incentive to “recommend to a friend”.

Results of Models

- Vary parameters to study sensitivity of uptake:
  - network types and parameters,
  - weights and thresholds.
- Simulate many randomisations to investigate stability of results.
- Study various "interventions":
  - initial conditions,
  - "incentives" to reduce thresholds etc.

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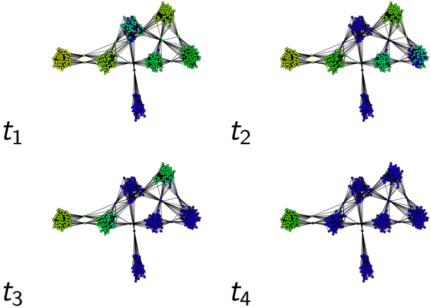
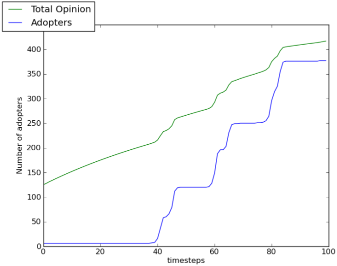
Example: Weighted "opinion" Model on Community Network





t_1=45, t_2=60, t_3=75, t_4=90

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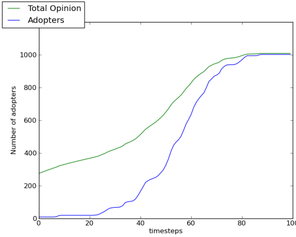
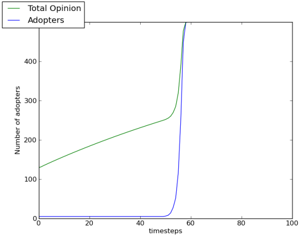
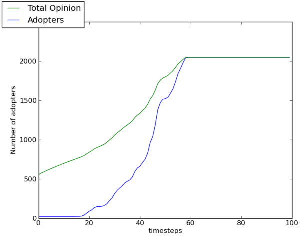
Comparing Different Transitions



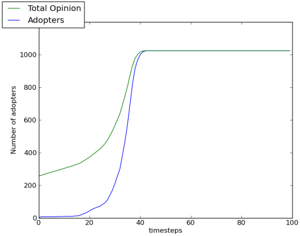
(a)



(b)



(c)



(d)

(a): Weakly connected communities. **(b)**: Inter-community *bridges*.

(c): Large, weakly bound groups. **(d)**: Distributions of thresholds.

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Possible Conclusions

In this simple example:

- Fast transitions are seen wherever tightly bound communities interact with more than a few others.
- Transition to technology adoption can be slowed when:
  - communities are not tightly bound,
  - communities do not interact strongly,
  - a lot of individuals have high resistance to uptake.
- To ensure a fast transition increase:
  - strength of links,
  - inter-community ties,
  - information about whole system.

Potential Recommendations

- Increase network ties for swift transition:
  - incentivise people to spread the word, e.g. by:
    - money back for recommending a friend,
    - money off for groups investing together.
- Make energy more visible to consumers, e.g.:
  - smart meters, showing neighbourhood averages, time-averaged individual (monthly/weekly) spend,
  - potential savings from EE measures,
  - show prevalence of EE measures in society to encourage people into the 'trend',
  - attract *early adopters* by predicting future trends.

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