The role of complex Infrastructure Systems and space in mediating global change

Frontiers of Global Change Science, 17 – 22 August 2014, Aspen, CO

Alex Otto
(Infra)Structure links the environmental with the socio-economic system.

We need to take Complexity far more seriously both when modelling integrated socio-technical-environmental systems and when trying to manage them.

A conceptualisation and method based on Information (and Evolution) can help to understand possible long-term dynamics of socio-technical-environmental systems.
My journey so far

The fun with Quantum Information is that you can study the foundations of the enigmatic world of Quantum Mechanics, and, at the same time, you make something useful for practical applications.

National infrastructure assessment: Analysis of options for infrastructure provision in Great Britain
Interim results, January 2014

2002  2007  2008  2011  2011  now
The Frontier for Integrated Assessment
Moss et al., The next generation of scenarios for climate change research and assessment Nature 463, 747-756
What is infrastructure?

Big lumpy stuff sticking in the ground.

or...

Characteristics of Infrastructures:

• Long gestation periods and lifetime.
• Contractual problems.
• Network effects.
• Foundational services.

Networks of assets providing foundational services for the functioning of the economy. (e.g. ITRC,...)
What is infrastructure?
Fields vs Hierarchical Networks
Indirect effects through interconnectedness

(Thacker, 2014)
Indirect effects through interconnectedness

Event Max Temp (°C)
- 28
- 29
- 30
- 31

Cost Increase (Minutes)
- 0 - 10.0
- 10.1 - 25.0
- 25.1 - 50.0
- 50.1 - 100.0
- 100.1 - 140.5

ARCADIA project  www.arcc-network.org.uk/project-summaries/arcadia/
Vulnerability & Resilience analysis of current Infrastructure systems

A. Spatially coherent hazard event

B. Topological network failures

C. Disruptions and economic losses

D. Risk estimation

Network reliability
- Asset fragility
  - < 0.4
  - 0.4 - 0.8
  - > 0.8

Multiple failure conditions

Multiple hazard events

Infrastructure loss

Risk = Probability × Loss

Macroeconomic economic flow losses
- Direct losses
- Indirect losses

Economic loss ($ million)

0 150 200
0.1 0.05 0.02 0.001

Hazard event probability

Risk ($ million)

0 50 100 150
0.1 0.05 0.02 0.001

Hazard event probability

Ranges of values

Spatially aggregated customers

Disrupted customers

Disrupted customers
What about the future?


Grady et al. Nature Communications, 2012

Grady et al. Nature Communications, 2012
• Many social and technical components  (Huges 1987)
• Parallel, distributed self organization with reflective downward causation  (Holland 1996, Kroes 2009)
• Evolve over time  (Dennet 1996, Dawkins )
• Require multiple formalisms to understand fully  (Mikulecky 2001)
• Are value and emotion loaded.  (Roesser 2012, van der Hoeve, 2012)
• Limited controllability

• The possibilities of projection, and planning are limited.

• An adaptive, inclusive, recursive management practise is required. (Robust rather then optimal decisions.)

• The role of modelling as forcasting has to be replaced.

• Model development as evolution of an “eco-system of models”
A convergence of fields

Infrastructure-Systems

Environmental-Economics  New-Economic-Geography  Network-Science

Ecological-Economics  Econo-Physics

Evolutionary-Economics  Constructual-Theory

Computational-Social-Science  Universal-Darwinism  Statistics

Post-Normal-Science
The Power of auto-catalysis

The Physical-Memetic Loop

Perception of the Environment

Ideas, Wishes, Plans

Complex Language

Technology embodies ideas

Infrastructure as collective Technology

Infrastructure as environment

(Pinker, 2012)
Multiple Sectors, Actors, Influences

Framing Effects

Issue linking

Social influence networks

Institutions

Memetic Space

Physical Space

Network Effect

Connectivity Effect

Physical scale effects

Economies of Scale
A Generic Model of Infrastructure System Evolution

Memetic space

Exergy space
Timescales of Change

Companies
Technologies
Climate
Infrastructures
Institutions
Culture
Thank You!

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What is infrastructure?

The Pornography Definition

I shall not today attempt further to define the kinds of material I understand to be embraced within that shorthand description ["hard-core pornography"]; and perhaps I could never succeed in intelligibly doing so. But I know it when I see it, and the motion picture involved in this case is not that.

—Justice Potter Stewart,
Concurring opinion in Jacobellis v. Ohio 278 U.S. 184 (1964)
Part I

What is integrated assessment?
Part I

What is integrated assessment?
Part I

What is integrated assessment?
**What is integrated assessment**

**Integrating** knowledge from different disciplines into a single framework

Aims to provide useful information for policy makers by **assessing** policy options
The Earth-System...

...is vastly complex...

...with massive interactions across all scales...

...with non-linear dynamics, and potentially abrupt transitions...

...combined with huge uncertainties.
Global surface temperature change and uncertainty

IPCC AR5, WG1, 2013
Global mean sea level rise and uncertainty

IPCC AR5, WG1, 2013
Tipping points and non-linearities

Lenton T M et al. PNAS 2008;105:1786-1793

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Increasing risk of climate change

Dutch cow ready for sea level rise?
The global economy...

... is growing very robustly...

... characterised by substitution of scarce resources through technological progress...

... has "just" to be informed about externalities like climate change by appropriate price signals.
Devaluation of fossil resources

Kalkuhl & Edenhofer 2010
Devaluation of fossil resources

- Atmosphere is a scarce resource – fossil carbon is not
- How to determine scarcity price on carbon?
  - Assigning property rights according to the scarcity of the atmosphere
  - Distributing the emission rights according to principles of fairness and justice

Resource Extraction

> 12,000 GtC

Atmosphere as a limited resource

~ 230 GtC
Cost Benefit analysis

Costs [\$] vs. \( \Delta T \) [\(^{\circ}\text{C}\)]

- **Mitigation**
- **Damages**
Framing different perceptions of Climate Change within CBA

- **CBA**
- **“fatalist”**
- **“environmentalist”**
- **“sceptic”**
Part II

Integrated Assessments of Climate Change
Questions for an IA of Climate Change

What is the optimal trade-off between mitigation and adaptation?

What is the social cost (net benefit) of a specific climate regime?

What is the relative importance of different mitigation options?

What is the (mitigation) cost of climate policy and how is it distributed?

Who are winners and losers of different climate regimes?

What are efficient strategies to implement climate mitigation policies?

How can we stabilise a climate coalition?
Examples of Integrated Assessments

Bill Nordhaus

1994

Stern Review

2000

IPCC AR4

Synthesis report

2007

IPCC AR5

2014

WG1

WG2

WG3

Nordhaus

The Climate Casino

Managing the Global Commons

UNIVERSITY OF OXFORD

eci
### Framing different perceptions of Climate Change within CBA

<table>
<thead>
<tr>
<th>WATER</th>
<th>Increased water availability in moist tropics and high latitudes</th>
<th>Decreasing water availability and increasing drought in mid-latitudes and semi-arid low latitudes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.4 to 1.7 billion</td>
<td>1.0 to 2.0 billion</td>
</tr>
<tr>
<td></td>
<td>1.1 to 3.2 billion</td>
<td>Additional people with increased water stress</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ECOSYSTEMS</th>
<th>Increasing amphibian extinction</th>
<th>About 20 to 30% species at increasingly high risk of extinction</th>
<th>Major extinctions around the globe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Increased coral bleaching</td>
<td>Most corals bleached</td>
<td>Terrestrial biosphere tends toward a net carbon source, as:</td>
</tr>
<tr>
<td></td>
<td>Increasing species range shifts and wildfire risk</td>
<td>Widespread coral mortality</td>
<td>~15%</td>
</tr>
<tr>
<td></td>
<td>Crop productivity</td>
<td>Low latitudes</td>
<td>~40% of ecosystems affected</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Decreases for some cereals</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increases for some cereals</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mid to high latitudes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Additional people at risk of coastal flooding each year</td>
<td>0 to 3 million</td>
<td>2 to 15 million</td>
</tr>
<tr>
<td></td>
<td>Increased damage from floods and storms</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>COAST</th>
<th>Increased burden from malnutrition, diarrhoeal, cardio-respiratory and infectious diseases</th>
<th>Increased morbidity and mortality from heatwaves, floods and droughts</th>
<th>Substantial burden on health services</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>13</td>
<td>14</td>
<td>16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HEALTH</th>
<th>Local retreat of ice in Greenland and West Antarctic</th>
<th>Long term commitment to several metres of sea-level rise due to ice sheet loss</th>
<th>Leading to reconfiguration of coastlines worldwide and inundation of low-lying areas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17</td>
<td>17</td>
<td>18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SINGULAR EVENTS</th>
<th>Ecosystem changes due to weakening of the meridional overturning circulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td></td>
</tr>
</tbody>
</table>
Connection points for mitigation action

- Population
  - Per Capita Production (GDP / Pop)
  - Energy Intensity (E / GDP)
  - Carbon Intensity (CO₂ / E)
- Life-Style Change Technologies
- Non-Fossil Energy
- CO₂ Capture at Plant (CCS)
- CO₂ Released (CO₂(A)/CO₂)
- Carbon Cycle
- Ocean Acidification
- Climate Change
  - 2º / 3º / 4º Policies
- Adaptation
- CO₂ Emissions
- Other GHG Emissions (Agricultural Practices etc.)
The cumulative picture... allows decoupling?
Part III

Integrated Assessment Modelling
Sectors incorporated in current IAMs

- Energy
- Climate
- Land-use
- Water
- Infra-structure
- Economy
- Resources
- Climate
The ecosystem of models

Physical Complexity

ABMs?

global land use
Models (MagPie, LPMJ-ML)

Welfare Optimising

CBA – models:
DICE, FUND, PAGE

CGE models

Economic Complexity

McGuffie & Henderson-Sellers, 2005, p51
The three dimensions of modelling

- **Macroeconomic completeness**
- **Technical explicitness**
- **Macroeconomic realism**

Grafic after Hourcade et al. (2006)
Simple CBA Integrated Assessment models

DICE model (Nordhaus, 1992)

Objective

Welfare based on per capita consumption

Decision

Production $Y(t) = Consumption\ C(t) + Investment\ I(t)$

Coupled System

Production

$Y(t) = \phi(t) K(t)^{\alpha} L(t)^{1-\alpha}$

- Damage cost function
- Energy efficiency increase
- Mitigation cost function
- Climate change
- Emissions
An example of an Economy-Energy-Climate model (REMIND)

Macroeconomic module
- Investments
- Consumption
- Output
  - Capital
  - Labour
  - Final energy
- R&D
- Labour efficiency
- R&D

Welfare

Energy system module
- Energy system costs
  - Fuel costs
  - Investment costs
  - Operation and Maintenance costs
- Learning by doing
- LUC/OGHG abatement costs

Energy transformations and conversion technologies
- Resource and potential constraints

Exogenous data
- Emissions
- Concentration
- Temperature

Climate module
An example of an Economy-Energy-Climate model (REMIND)
The energy system in REMIND

**Primary Energy**

- Fossil Fuels
  - Crude Oil
  - Coal
  - Natural Gas

- Uranium

- Renewables
  - Solar
  - Hydro
  - Wind
  - Geo

- Biomass

**Secondary Energy**

- Refinery (4 types)
  - Gas purification
  - Coal to Gas, Biomass to Gas
  - Coal to Solids, Biomass to Solids

- Diesel Oil Turbine
  - Coal: IGCC, PC, CHP
  - Natural Gas: NGCC, NGT, CHP
  - Biomass: CHP
  - Nuclear: LWR, FBR

- Solar/Wind (on/offshore), Hydro, Geo

- Coal HP, Gas HP, Biomass HP

**Final Energy**

- Heating Oil
  - for households
  - for industry

- Transport Fuels
  - Petrol, Diesel
  - for transport

- Gas
  - for households
  - for industry

- Solids
  - for households
  - for industry

- Electricity
  - for households
  - for industry

- District Heat
  - for households

- Hydrogen
  - for households
  - for industry
  - for transport
Mitigation options in the REMIND model

Business-as-usual vs. 2°C policy target

ReMIND model results
Bauer et al., 2010
Inter-model comparisons - RECIPE

Primary Energy Mix

IMAACLIM-R
Energy Mix, IMAACLIM, WORLD, baseline

ReMIND-R
Energy Mix, REMIND, WORLD, baseline

WITCH
Energy Mix, WITCH, WORLD, baseline

Baseline

Primary energy [EJ]

2005 2020 2040 2060 2080 2100

IMACLIM-R

ReMIND-R

WITCH

Luderer et al., 2009
Inter-model comparisons - RECIPE

Investment Mix

**IMACLIM-R**

**ReMIND-R**

**WITCH**

Investment Mixes for different scenarios and models, showcasing investments in various sectors over time.

Luderer et al., 2009
Feasibility and Cost of meeting climate targets

400 ppm neither achievable without CCS nor without extension of renewables
Biomass potential dominates the mitigation costs of low stabilisation

Knopf et al. (2009)
Edenhofer et al. (2010)
The cost of delayed action

- delay of action beyond 2020 makes climate target unachievable
- decreasing costs with increasing participation in climate coalition

Luderer et al., 2009; Jakob et al., 2011.
The case for early action

Early action advantage: Benefit of anticipation outweighs costs of more ambitious abatement

Luderer et al., 2009; Jakob et al., 2011.
Mitigation implies redistribution of wealth from fossil fuel owners to owners of emission allowances.
Part IV
Criticism, Challenges, and next steps
Increasing realism:
• Integrating uncertainty & Learning
• Multiple decision makers
• Multiple externalities
• Second best solutions & policy instruments
• The growth framework
• Higher spatial & Sectoral resolution
• Robustness and adaptive decision making
Essential components for a comprehensive integrated assessment

Energy
Information
Infrastructure
Resources
Innovation
Non-rationality
Imperfect economy
Uncertainty
Monetary policy
...

Energy
Economy
Land-use
Infra-structure
Resources
Climate
Water
The doughnut economy
Innovation, Information, Technology

Waves of Innovation

1st wave
- Iron
- Water power
- Mechanisation
- Textiles
- Commerce

2nd wave
- Steam power
- Railroad
- Steel
- Cotton

3rd wave
- Electricity
- Chemicals
- Internal combustion engine

4th wave
- Petrochemicals
- Electronics
- Aviation
- Space

5th wave
- Digital Networks
- Biotechnology
- Software
- Information technology

6th wave
- Sustainability
- Radical resource productivity
- Whole system design
- Biomimicry
- Green chemistry
- Industrial ecology
- Renewable energy
- Green nanotechnology

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Next Steps – e.g. The SCiRM project
The integrated Assessment of Climate Change is bringing together different perspectives on the climate problem.

It can give formal insights into necessary trade-offs for optimal global mitigation strategies.

It can emphasise the political and technological challenges of climate change.

It cannot (yet) derive “practical solutions”.
Entry points to further reading

Integrated Assessment of Climate Change

IPCC AR5, Summary for Policy Makers (www.ipcc.ch)

Climate Impacts


Integrated Assessment Models / Limitations

Community Integrated Assessment System (CIAS) (http://www.tyndall.ac.uk/research/cias)

Pindyck, R.S., 2014, Climate Change Policy: What do the models tell us?, NBER WP 19244