The cost of cascading failure

risk and resilience within UK infrastructure networks

4CMR | Department of Land Economy

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Agenda

1. Infrastructure and the UK economy
2. Input-Output analysis of UK infrastructure
3. Results from ITRC hotspot analysis
4. MonteCarlo simulations of cascading infrastructure failure

Research Objectives

ITRC WS2 Objective:

> *"Develop network models to analyse the vulnerability of interdependent infrastructure systems and the risks of infrastructure to people and the economy, in present and future climate and socio-economic scenarios"*

ITRC Deliverable 2.6:

> ***"An input-output analysis of the consequences of infrastructure failure for present and future economic scenarios"***

Research questions

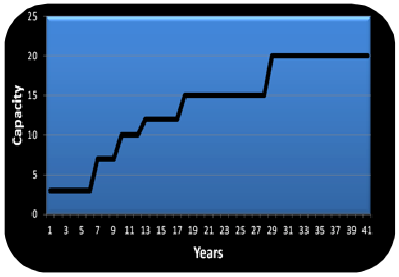
- What is the contribution of infrastructure to the UK economy?
- What are the interdependencies between infrastructure service sectors and other economic sectors?
- What are the economic losses (indirect + direct) resulting from infrastructure failure?
- What is the best way to estimate variability and uncertainty in the underlying impact distributions?

PART 1

Infrastructure and the economy

Eight defining characteristics of infrastructure systems

Provides a service



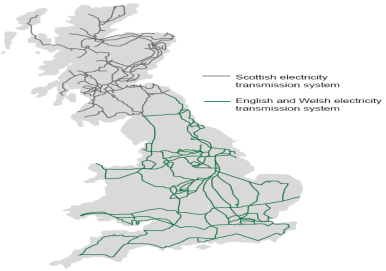
Lumpy

Long lasting

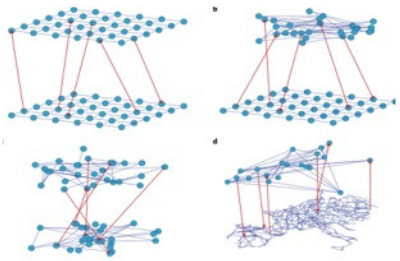
Immobile

Natural monopoly

Used by end consumers and by industry



Part of a network



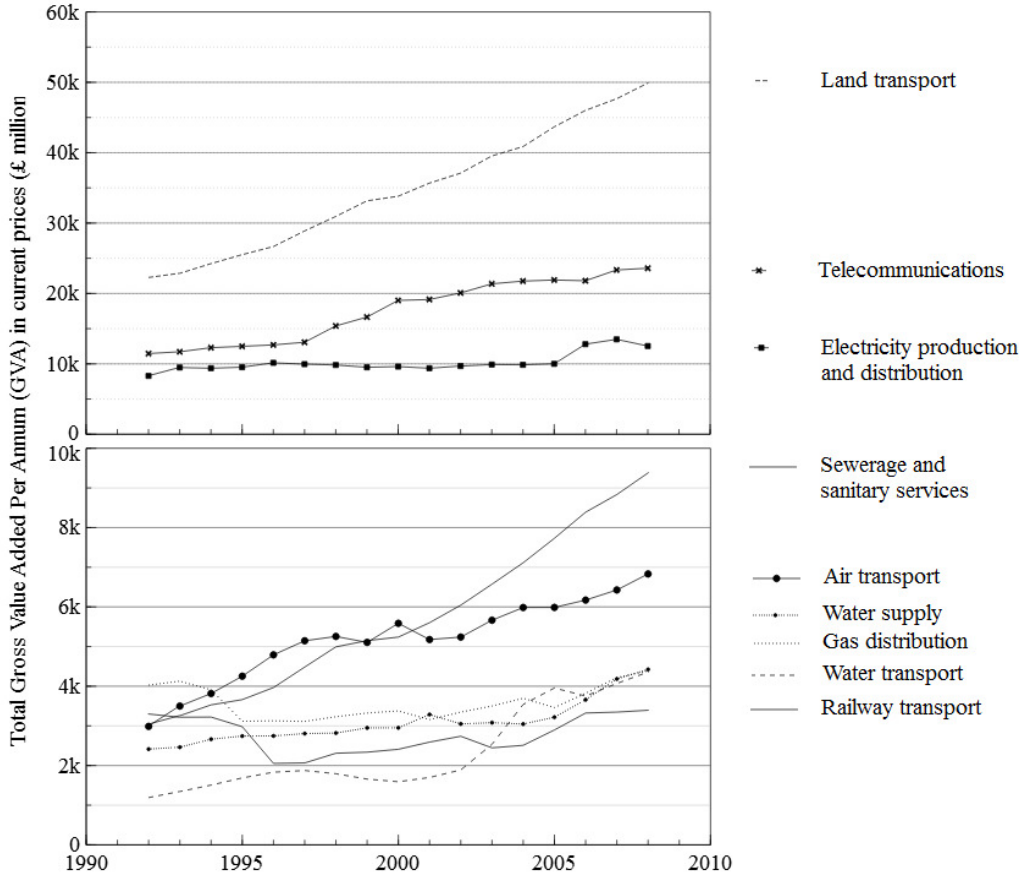
Interdependent

Economics of UK Infrastructure

Infrastructure services contribute to 9.2% of UK GDP

SIC(2003)	Sector (£2008)	GVA(1992) (£million)	GVA(2004) (£million)	GVA(2008) (£million)	Change in GVA (1992 - 2008) (£million)	% Growth (1992-2008)
85	Electricity and distribution	£8,288	£10,061	£12,533	£4,245	51.2%
86	Gas distribution	£4,026	£3,886	£4,386	£360	8.9%
87	Water supply	£2,414	£3,156	£4,423	£2,009	83.2%
119	Sewerage and sanitary services	£3,040	£7,227	£9,379	£6,339	208.5%
99	Telecommunications	£11,456	£21,296	£23,585	£12,129	105.9%
93	Railway	£3,301	£2,321	£3,394	£93	2.8%
94	Land transport	£11,591	£19,005	£21,252	£9,661	83.3%
95	Water transport	£1,188	£3,399	£4,357	£3,169	266.8%
96	Air transport	£2,987	£6,089	£6,831	£3,844	128.7%
UK Totals		£547,495	£1,044,165	£1,295,663	£748,168	136.7%

Contribution of infrastructure services to UK economic activity

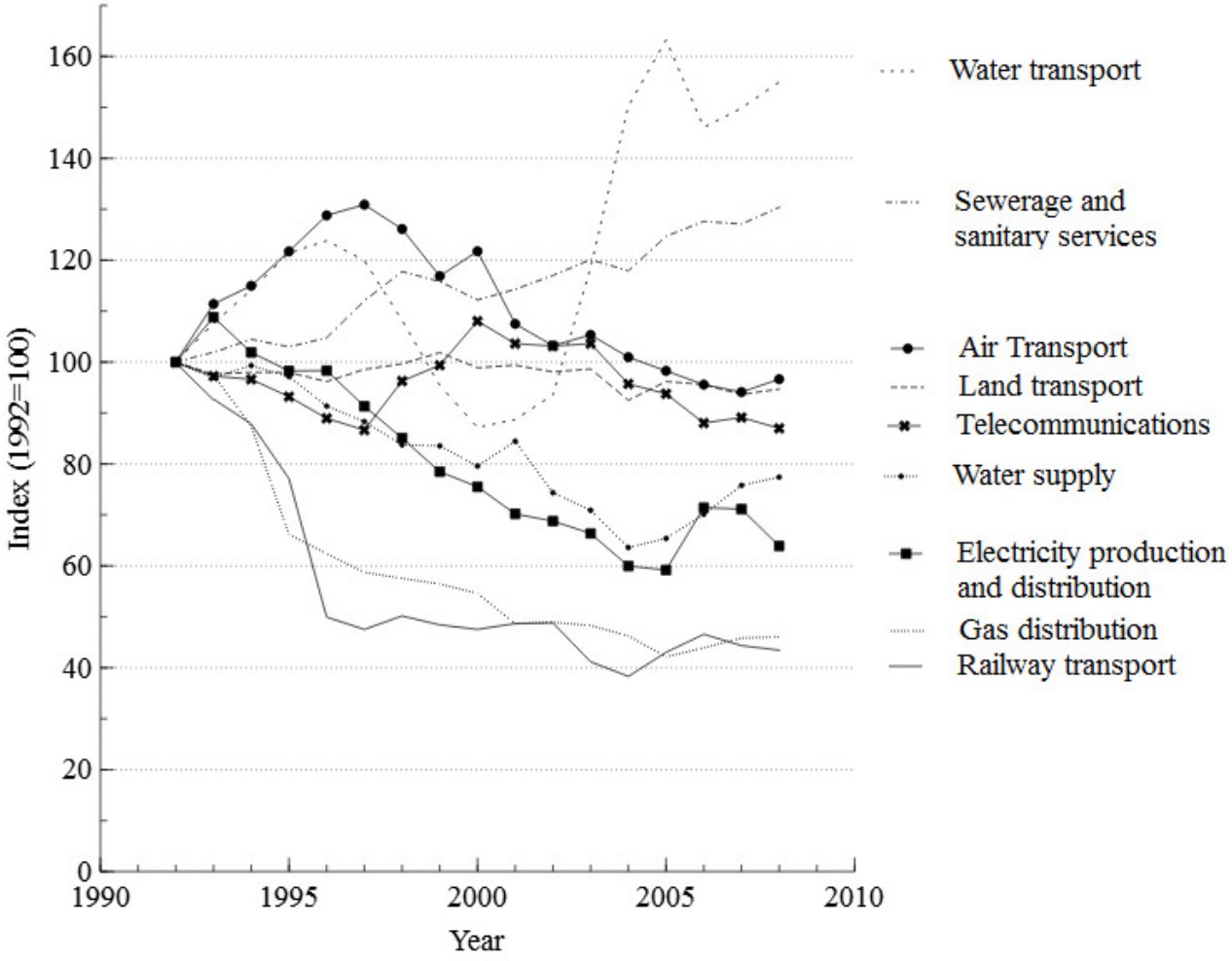


Infrastructure sector	GVA at basic prices (£ million)		GVA as percentage of total GVA	
	1992	2008	1992	2008
Electricity production and distribution	8,288	12,533	1.51	0.97
Gas distribution	4,026	4,386	0.74	0.34
Water supply	2,414	4,423	0.44	0.34
Land transport	22,261	49,887	4.07	3.85
Railway transport	3,301	3,394	0.60	0.26
Water transport	1,188	4,357	0.22	0.34
Air transport	2,987	6,831	0.55	0.53
Telecommunications	11,456	23,585	2.09	1.82
Sewerage and sanitary services	3,040	9,379	0.56	0.72

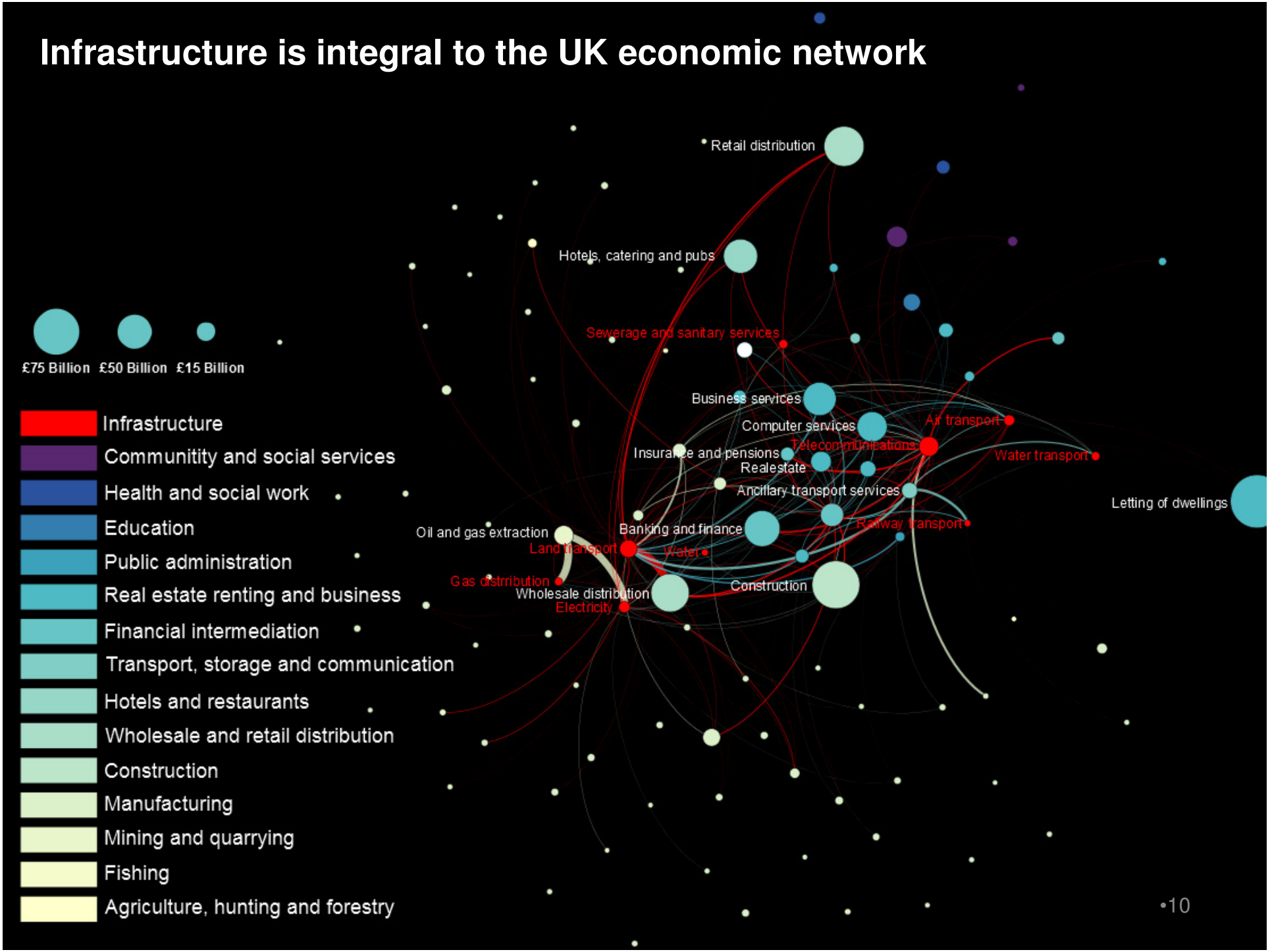
Relative contribution of UK infrastructure to GVA between 1992 and 2008 at basic prices[1]

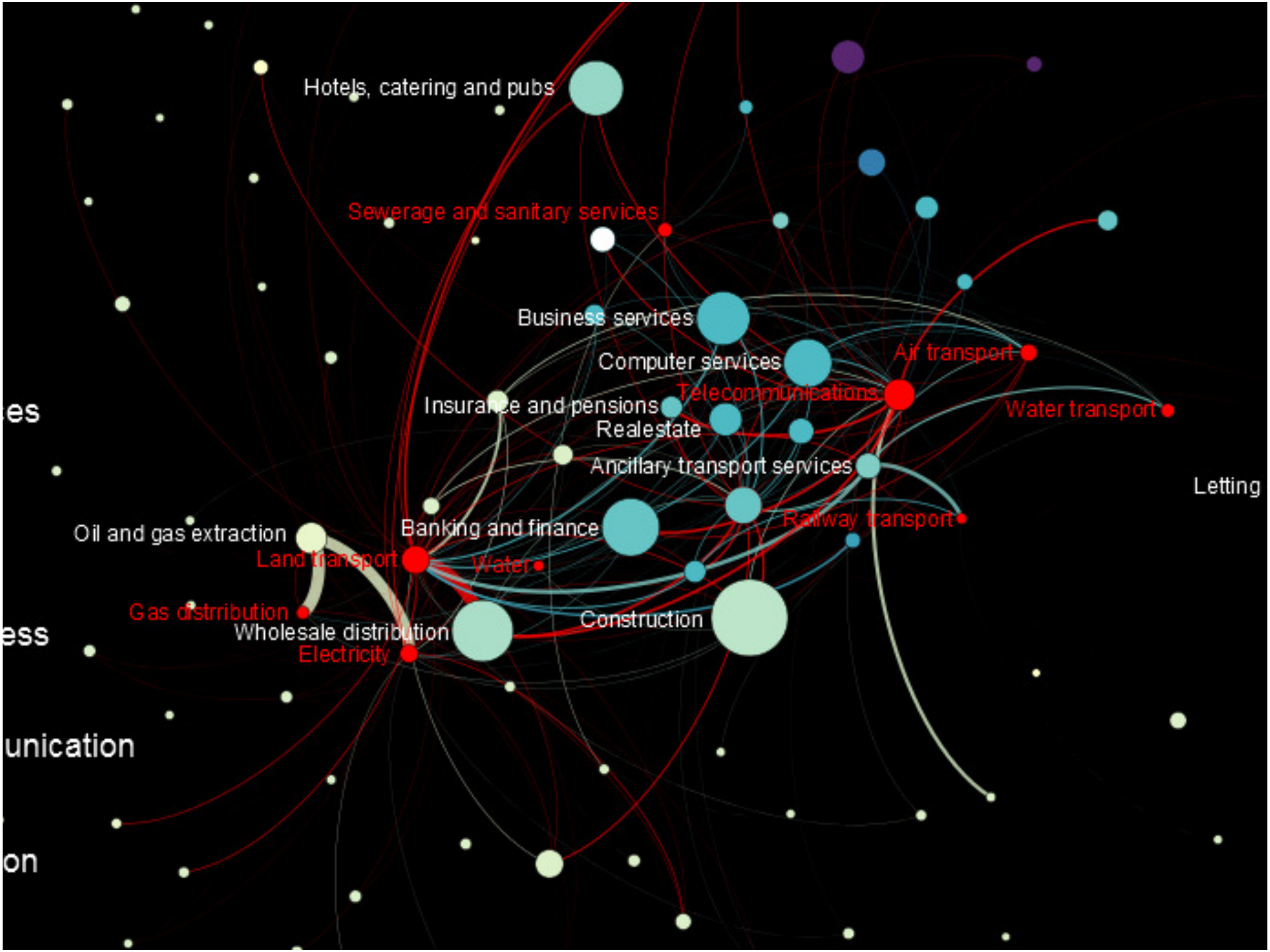
•Basic prices are the amount received by the producer for the purchase of a unit of good or service produced minus any tax payable and plus any subsidy receivable. It excludes transport charges invoiced separately by the producer.

Relative contribution of infrastructure services to UK economic activity



Infrastructure is integral to the UK economic network




Hotels, catering and pubs
Sewerage and sanitary services
Business services
Computer services
Air transport
Telecommunications
Insurance and pensions
Realestate
Water transport
Ancillary transport services
Letting
Oil and gas extraction
Banking and finance
Railway transport
Land transport
Water
Gas distrribution
Wholesale distribution
Electricity
Construction
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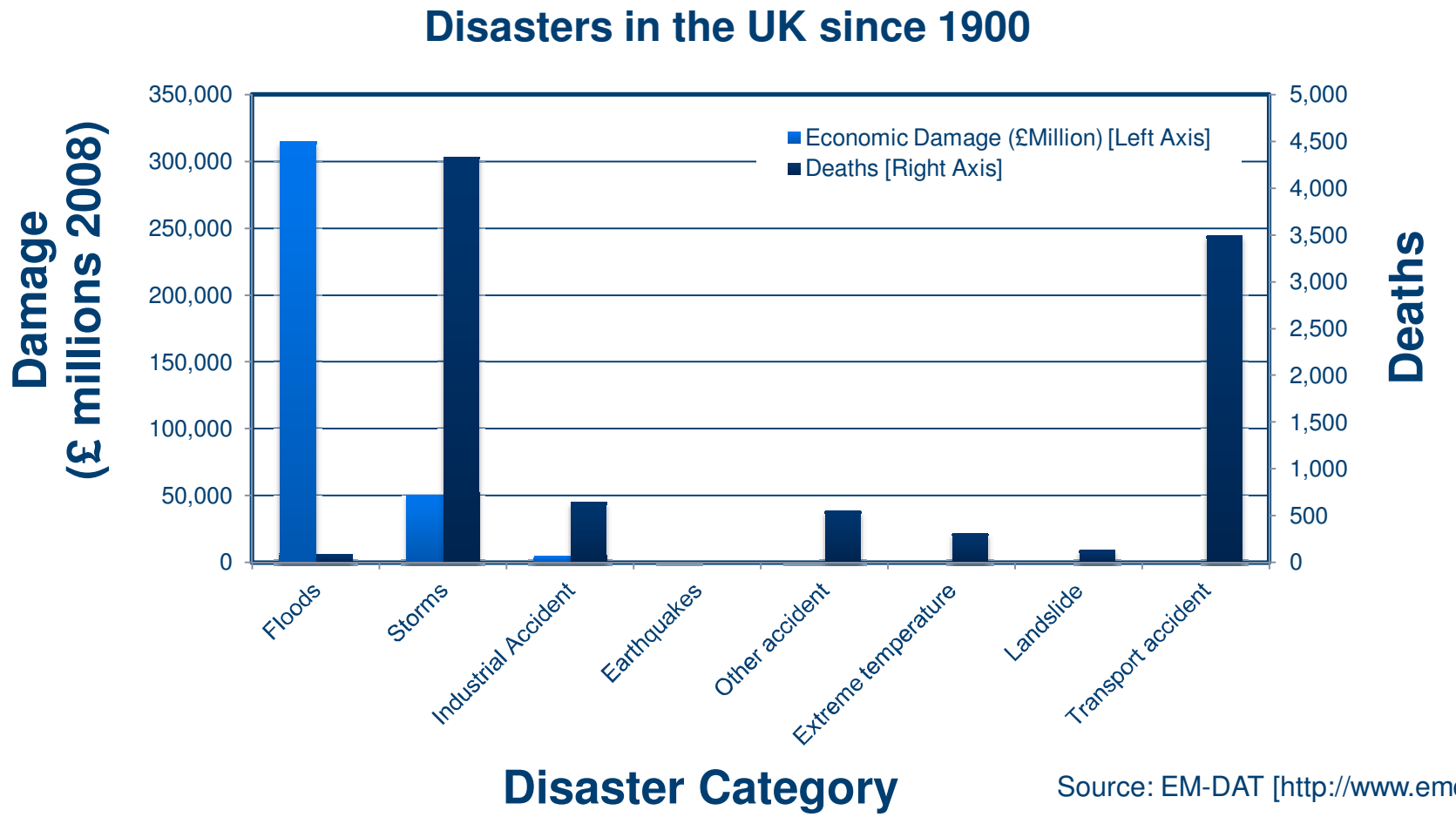
PART 2

Input output analysis and modeling the economic impact of disasters

Historical catalogue of 177 UK disasters



Source: EM-DAT [http://www.emdat.be/]

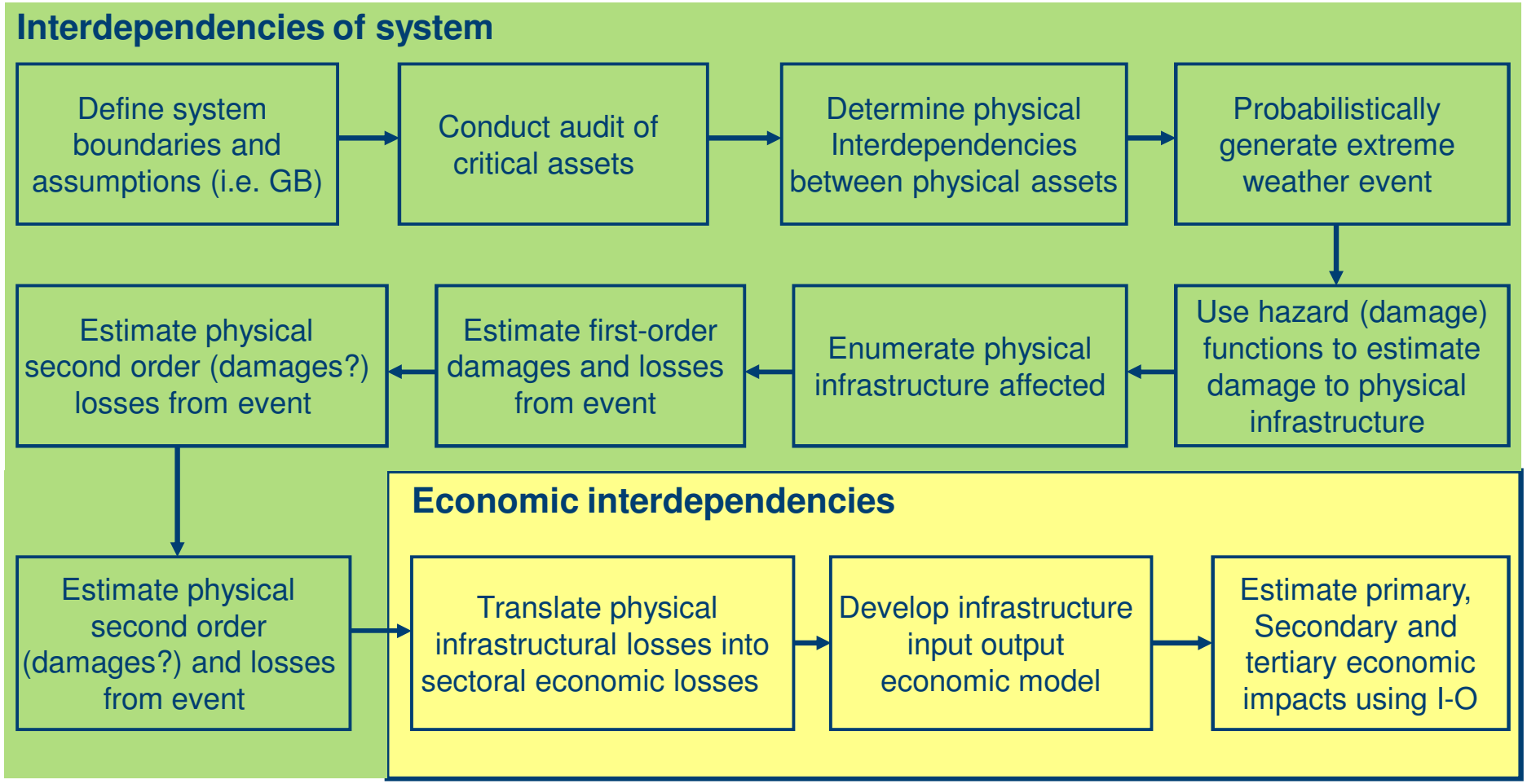
Effects of extreme events using IO analysis

- Extreme events result in both direct and indirect costs (Haimes and Santos 2005)
- Indirect losses can (sometimes) be greater than direct losses (Rose 2004)
- Disasters can cause backward propagation and forward propagation (Baade et al. 2007).
- Damage to 'lifelines' can have a significant economic impact (Cole 2003, Rose and Liao 2005).
- Bottlenecks in the system may limit economic recovery (Bockarjova 2007, van der Veen et al., 2003).
- The size and severity of the initial shock are important determinants of losses and recovery times (Bockarjova 2007)
- Economic resilience can be improved through substitution, inventories, unused capital or serving alternative markets (Cochrane 2003)
- Research is required to understand indirect economic impacts (Okuyama 2008)

Many economic studies of extreme events

- Hurricane Katrina (Hallegatte 2008)
- Terrestrial flood events in Mumbai (Ranger 2011);
- Drought events in South Dakota (Diersen and Taylor 2003)
- Drought events in Canada (Wheaton 2005, 2008)
- Coastal flood risks in Copenhagen due to climate change (Hallegatte 2011)
- Japanese Fukushima Daiichi nuclear disaster (Arto 2011; Shimoda 2011)

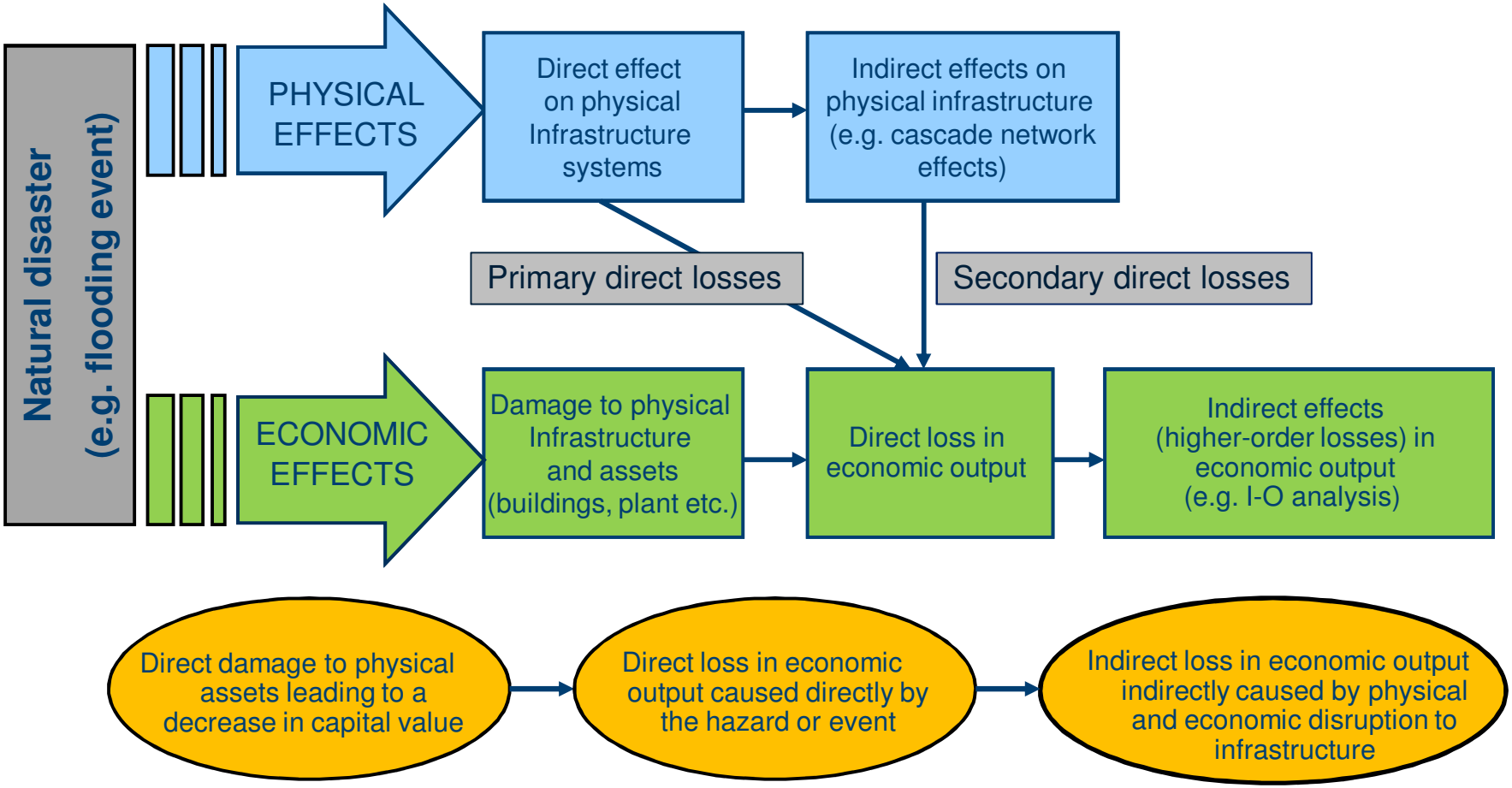
ITRC Process flowchart



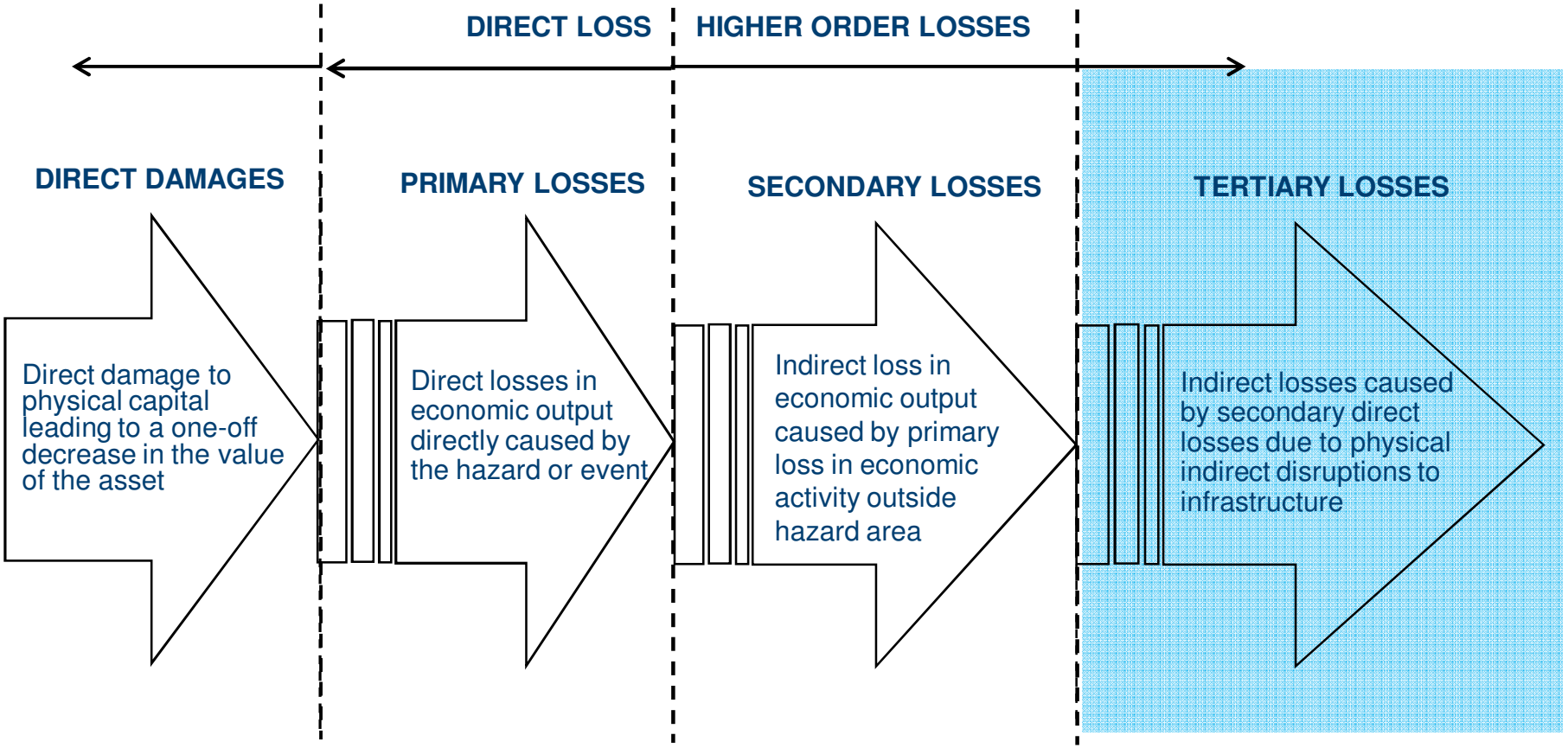
First order and higher order effects (stocks and flows)

Type of effect	Physical effect	Economic effect	Non-market effects
First-order effects (direct effects)	Infrastructure damaged directly by disaster (e.g. flooded power station)	**Damage** to capital and inventories and **economic loss** in output occurring directly due disaster	Loss of life, health impacts, loss in ecosystem services, loss of historic buildings etc.
Higher-order effects (indirect effects)	Infrastructure indirectly affected by disaster (e.g. pumping station outside of affected zone)	Higher-order economic effects on the economy due to the economic multiplier effect (e.g. requires IO analysis)	Impacts to the environment or human health outside the area directly affected by the disaster (e.g. contamination of food supply stocks due a nuclear disaster)

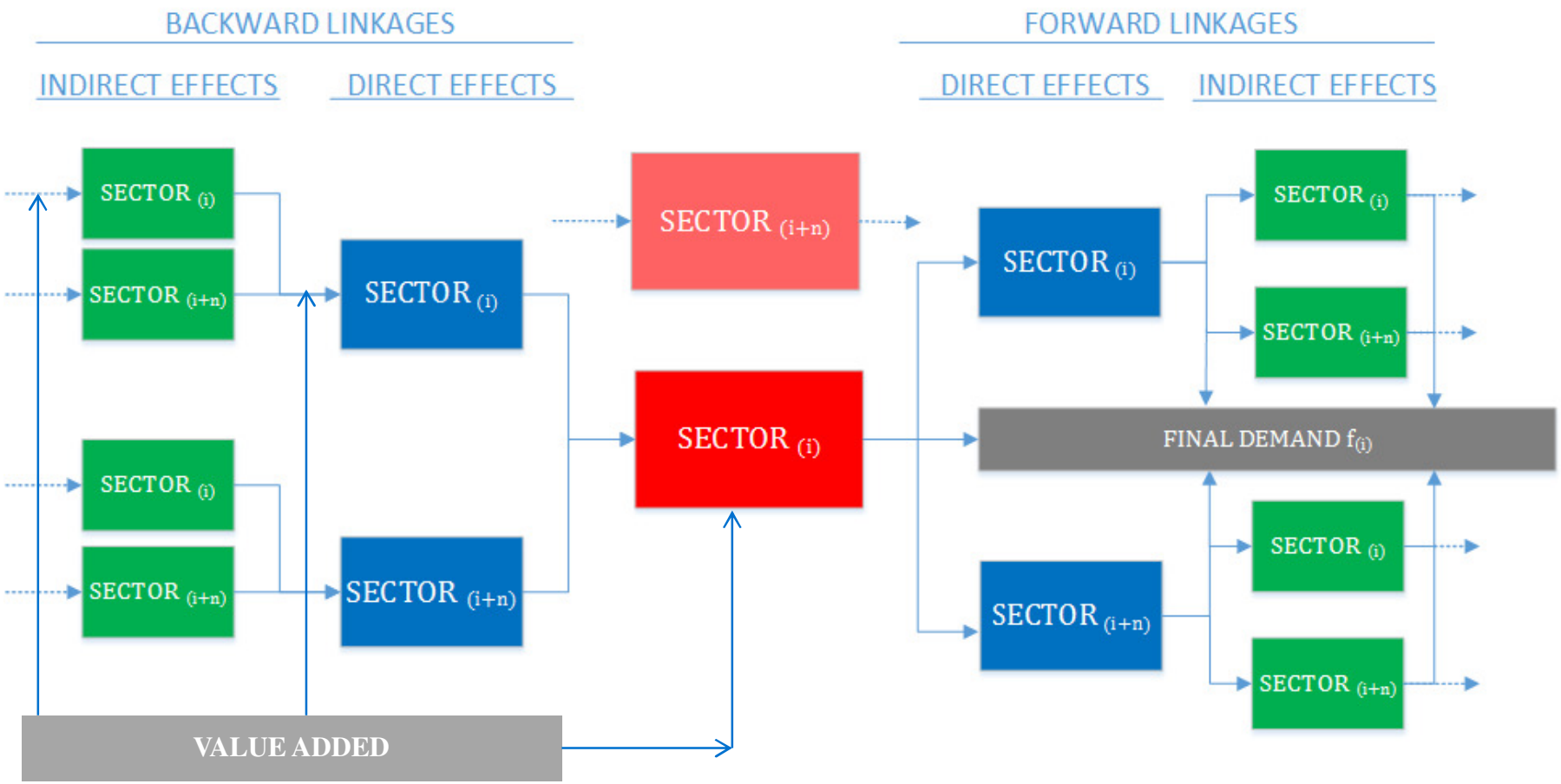
ITRC definition of physical and economic effects



Economic effects caused by disasters



Backward and forward linkages in the economy



Standard I-O classification table

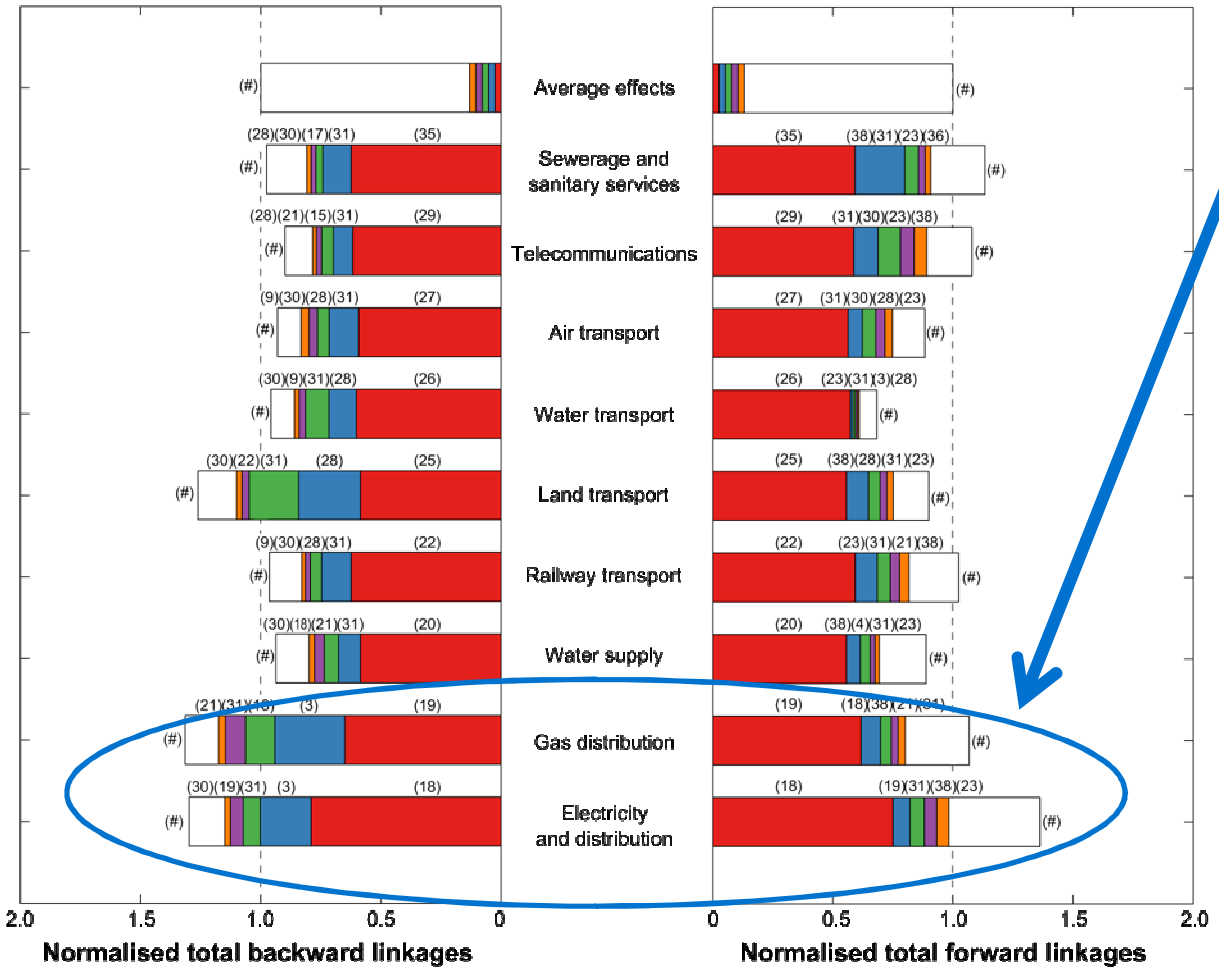
		PRODUCERS AS CONSUMERS								FINAL DEMAND			
		Agric.	Mining	Const.	Manuf.	Trade	Transp.	Services	Other	Personal Consumption Expenditures	Gross Private Domestic Investment	Govt. Purchases of Goods & Services	Net Exports of Goods & Services
PRODUCERS	Agriculture												
	Mining												
	Construction												
	Manufacturing												
	Trade												
	Transportation												
	Services												
	Other Industry												
VALUE ADDED	Employees	Employee compensation								GROSS DOMESTIC PRODUCT			
	Business Owners and Capital	Profit-type income and capital consumption allowances											
	Government	Indirect business taxes											

Figure 1.1 Input–Output Transactions Table

Sectors of the UK economy

1	Agriculture and forestry	14	Machinery	27	Air transport
2	Fishing	15	Electrical equipment	28	Postal and courier services
3	Coal, gas mining extraction	16	Motor vehicles, ship building and repair	29	Telecommunications
4	Food processing	17	Furniture, jewerly, sports equipment, toys	30	Banking finance, insurance
5	Textile and fabrics	18	Electricity production and distribution	31	Business services and real estate
6	Leather goods	19	Gas distribution	32	Public administration and defence
7	Wood and wood products	20	Water supply	33	Education
8	Pulp paper and paperboard	21	Construction	34	Health, vetenary, social work
9	Coke ovens, refined petroleum & nuclear fuel	23	Wholsale and retail distribtution	35	Sewerage and sanitary services
10	Industrial products, fertilisers, dyes, soaps, toiletries	24	Hotels and restaurants	36	Recreational and other services
11	Rubber and plastic products	25	Railway transport	37	Private households
12	Glass, ceramics, stone	22	Land transport	38	NPISH
13	Metal products	26	Water transport		

Key-linkages



Above average backward and forward linkages

Economic interconnectedness of infrastructure

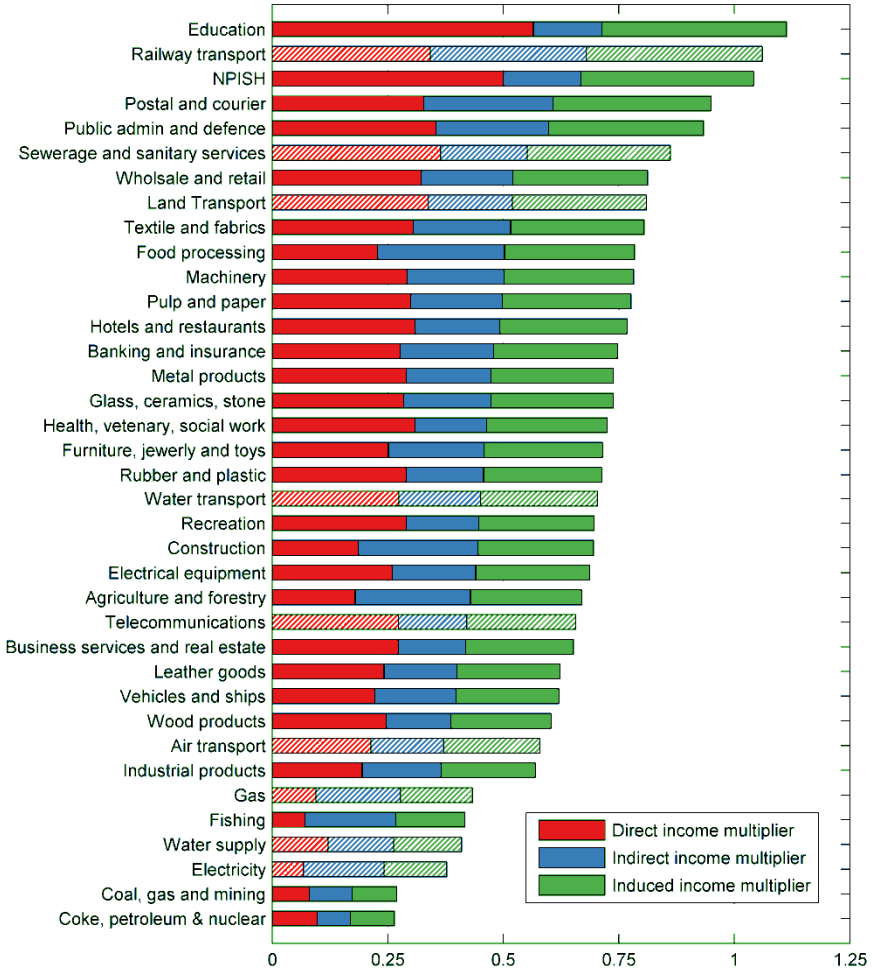
		Net Total Forward Linkages	
		Low(<1)	**High (>1)**
Total backward linkages	**Low (<1)**	Water supply Water transport Air transport	Telecommunications Sewerage and sanitation Railway transport
	High (>1)	Railway transport Land transport	Electricity production Gas distribution

Estimated economic value of infrastructure

	Estimated value to economy based on final demand	Estimated value to economy based on intermediate demand	Total value to the UK economy	Value as percentage of total output
	(£billion)	(£billion)	(£billion)	%
(18) Electricity production and distribution	8.77	44.41	53.18	2.36
(19) Gas distribution	10.22	29.63	39.84	1.76
(20) Water supply	2.99	4.58	7.57	0.34
(22) Land transport	43.06	92.11	135.6	5.99
(25) Railway transport	5.14	12.64	17.78	0.79
(26) Water transport	8.39	7.04	15.43	0.68
(27) Air transport	10.45	13.86	24.30	1.08
(29) Telecommunications	17.05	38.91	55.96	2.48
(35) Sewerage and sanitary services	3.29	14.55	17.84	0.79

- Values estimated using hypothetical extraction method
- Provides estimate of round by round contribution to the economy
- Estimates the contribution of economic activity from both intermediate demand and final demand

Employment (income multipliers)

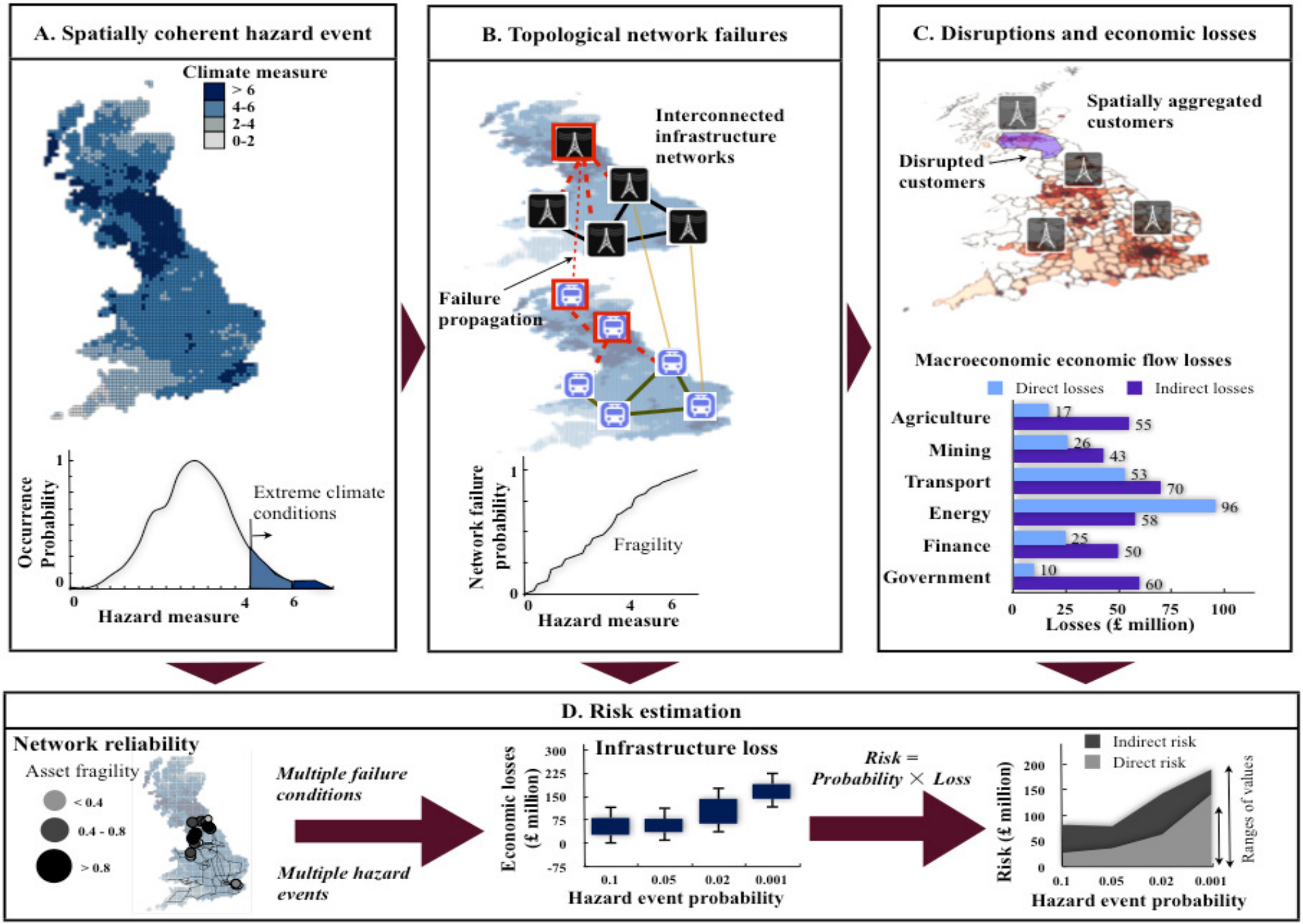


- Railway transport has largest overall income multiplier effect
- Electricity and Gas have largest Type I and Type II multiplier effects.
- The average multiplier effect across all infrastructure sectors is higher than the economy average.

PART 1

ITRC Hot Spot Analysis

System-of-systems risk analysis framework

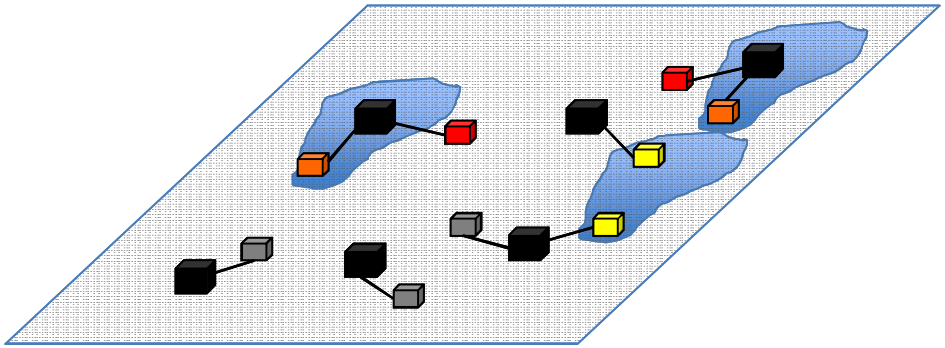


Infrastructure Asset Vulnerability Characterization

Overview and Sample Output

Characterising the vulnerability of England's major Infrastructure assets

- Dependency on nearest electricity substation
- Infrastructure data: ITRC database (England)
- Flood hazard map data: Cranfield NPD
- Vulnerable if located in flood area



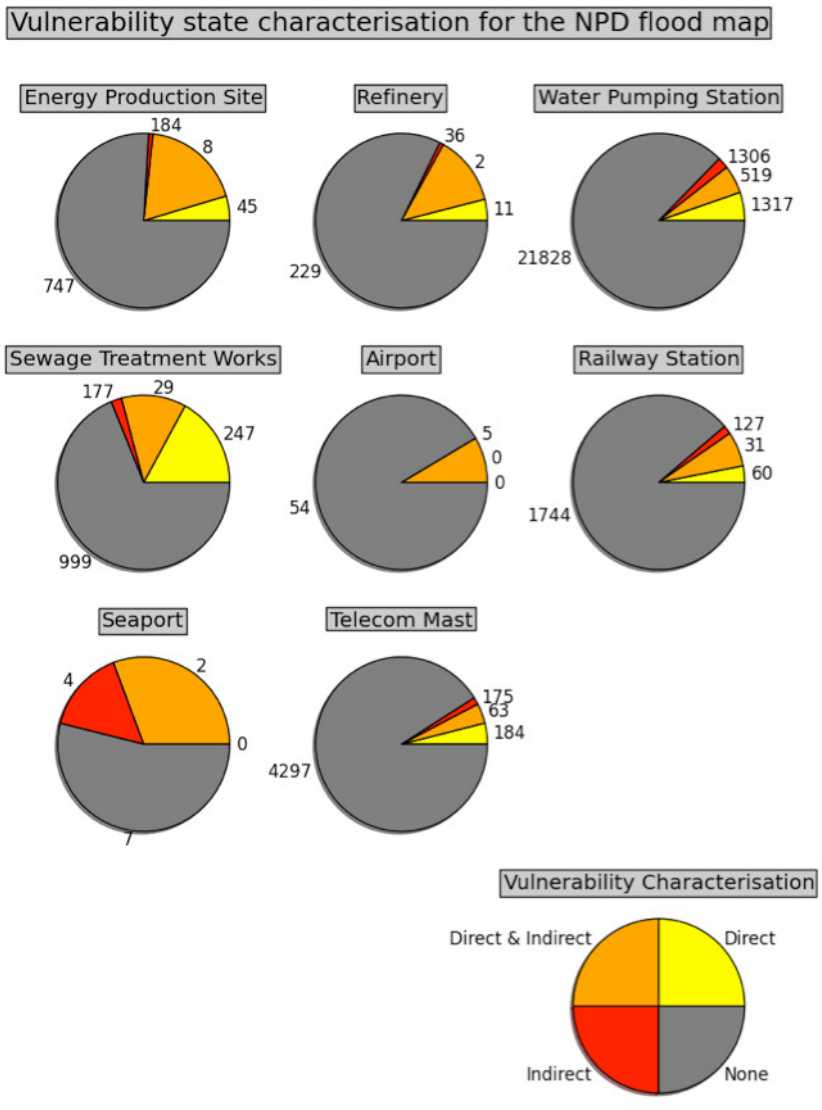
Electricity substation

Asset – Not Vulnerable

Asset – Directly Vulnerable Only

Asset – Indirectly Vulnerable Only

Asset – Directly & Indirectly Vulnerable



The standard IO models

We know, $\mathbf{Zi} = \mathbf{Ax}$ and $\mathbf{x} = \mathbf{Zi} + \mathbf{f}$ so…..

$\mathbf{x} = \mathbf{Ax} + \mathbf{f}$ rearrange equation so total output is all on LHS

$$\mathbf{x} = \mathbf{Lf} \qquad \Delta\mathbf{x} = \mathbf{L}\Delta\mathbf{f}$$

Standard Leontief

$$\mathbf{x}' = \mathbf{v}'\mathbf{G} \qquad \Delta\mathbf{x}' = \Delta\mathbf{v}'\mathbf{G}$$

Ghosh supply side

$$\mathbf{q}' = \left(\mathbf{I} - \mathbf{A}^*\right)^{-1}\mathbf{c}^*$$

Inoperability model

A new infrastructure input output model

We define, $\mathbf{L}_1 = (\mathbf{I} - \mathbf{A}_1)^{-1}$ where $\mathbf{A}_1 = \overline{\mathbf{A}}_{(-j,\,:)}$

Therefore, $\mathbf{L}_1$ is a unique solution for infrastructure j and without feedback effects back onto itself and so on…

Now we define, $\Delta\mathbf{f}_1$ as the direct impact on infrastructure j

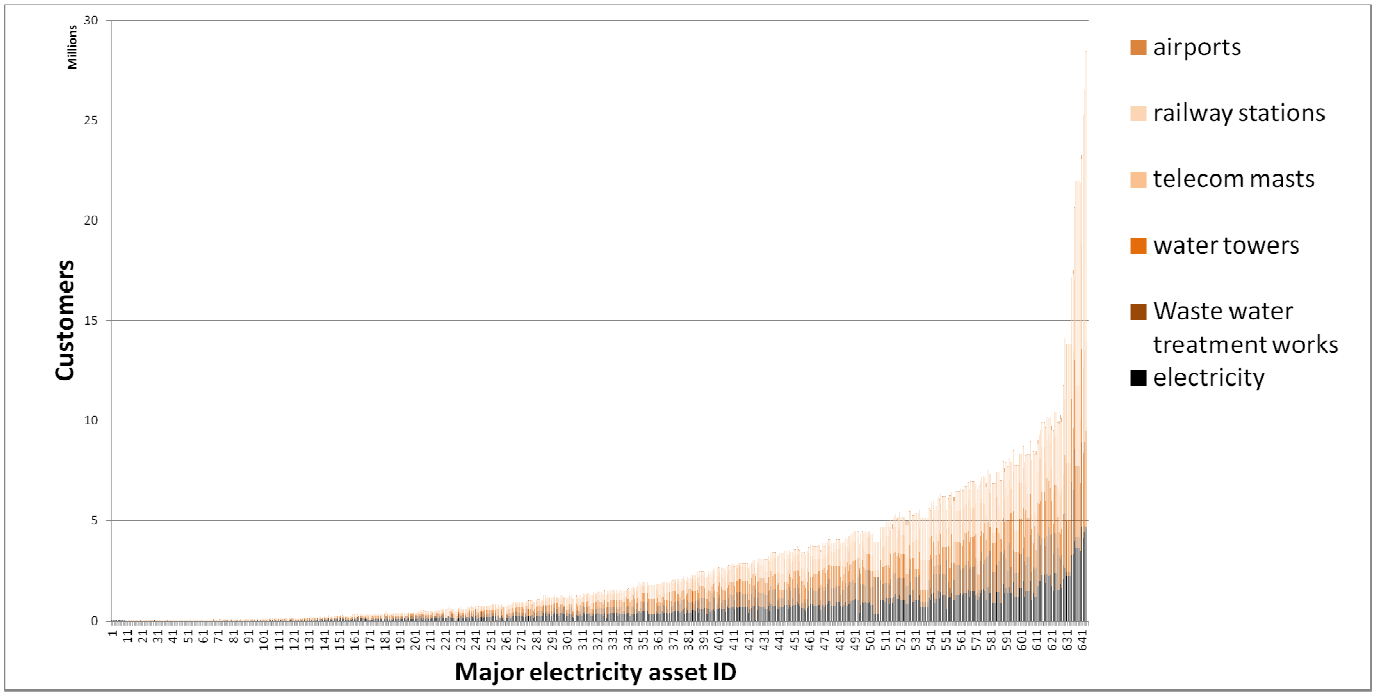
$\Delta\mathbf{x}_1 = \mathbf{L}_1\Delta\mathbf{f}_1$ Is the total impact from infrastructure j on the economy (direct + indirect impacts)

$$\Delta\mathbf{x}_{total} = \mathbf{L}_1\Delta\mathbf{f}_1 + \mathbf{L}_2\Delta\mathbf{f}_2 + \mathbf{L}_3\Delta\mathbf{f}_3 + \mathbf{L}_4\Delta\mathbf{f}_4 \ldots$$

$$\Delta\mathbf{x}_{direct} = \Delta\mathbf{f}_1 + \Delta\mathbf{f}_2 + \Delta\mathbf{f}_3 + \Delta\mathbf{f}_4 \ldots$$

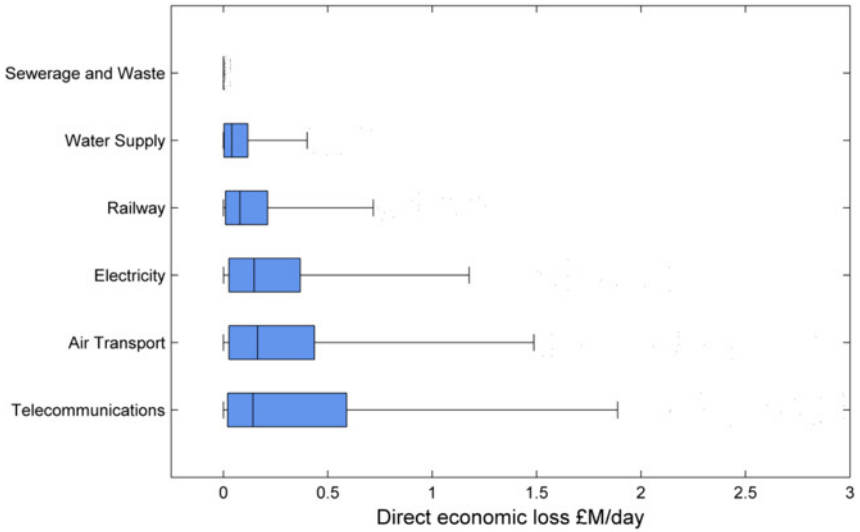
$$\Delta\mathbf{x}_{indirect} = \Delta\mathbf{x}_T - \Delta\mathbf{f}_1 - \Delta\mathbf{f}_2 - \Delta\mathbf{f}_3 - \Delta\mathbf{f}_4 \ldots$$

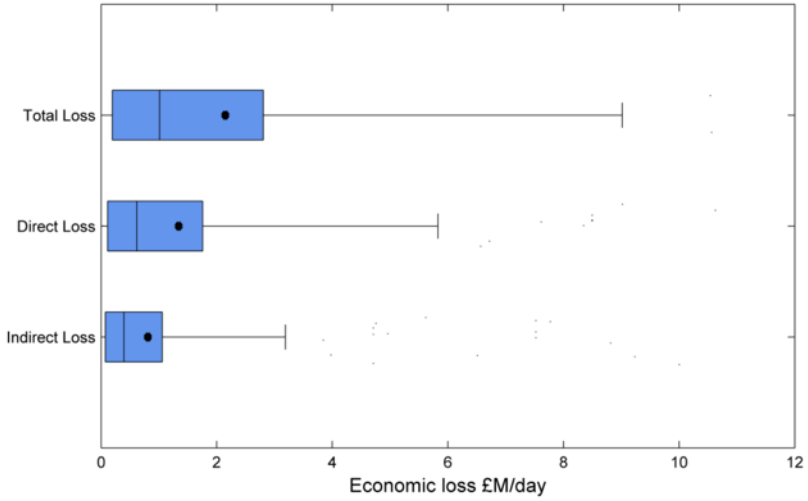
Customers affected by electricity asset failure

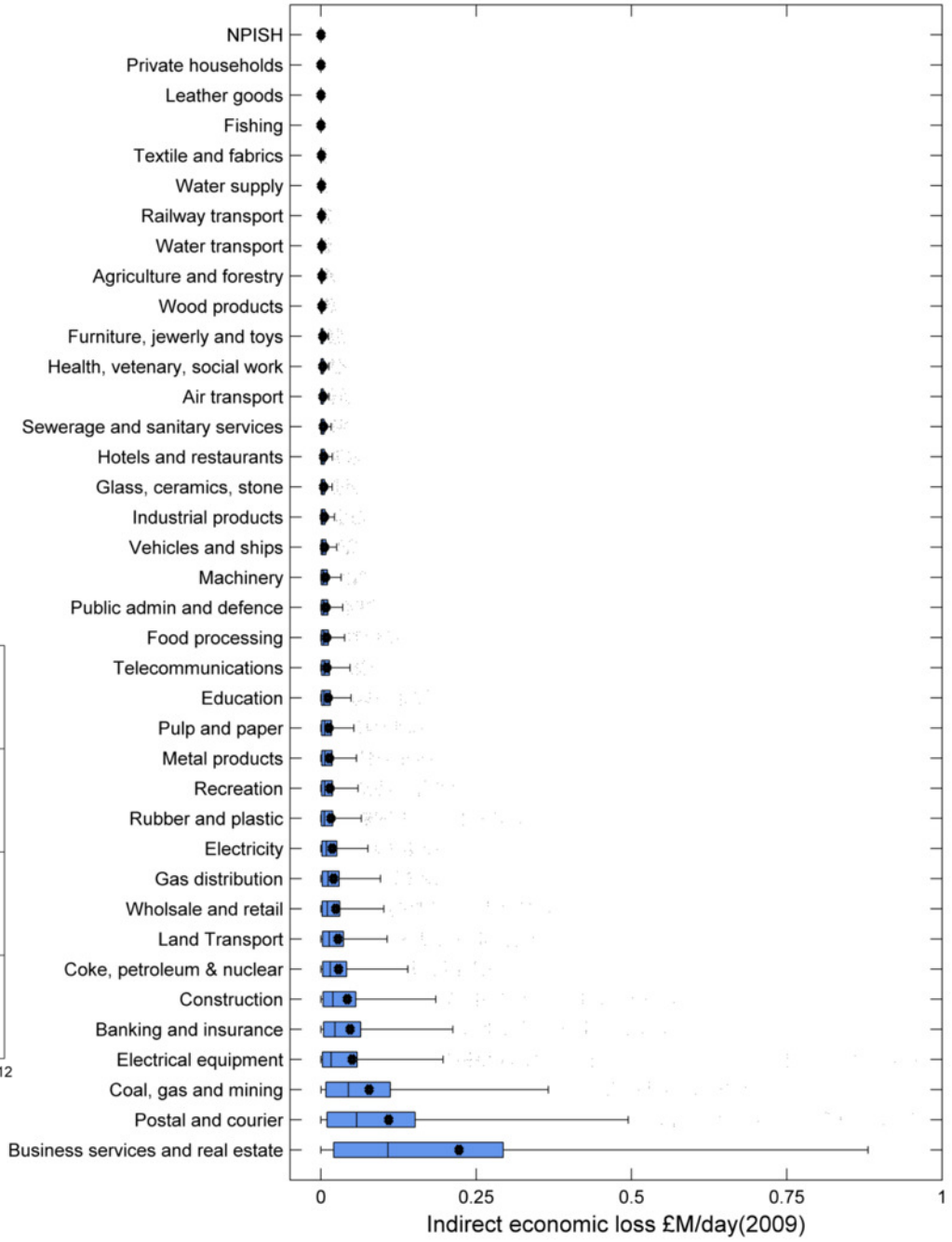


$$Y_{i,t_f} = \frac{C_{i,t=2}}{C_{i,t=1}} Y_{i,t_0}$$; where $\frac{C_{i,t=2}}{C_{i,t=1}}$ is ratio of customers affected by the disaster

Y_{i,t_0} and Y_{i,t_f} are the value of final demand for sector i at t_0 and t_1


Sewerage and Waste
Water Supply
Railway
Electricity
Air Transport
Telecommunications
0
0.5
1
1.5
2
2.5
3
Direct economic loss £M/day


Total Loss
Direct Loss
Indirect Loss
0
2
4
6
8
10
12
Economic loss £M/day


NPISH
Private households
Leather goods
Fishing
Textile and fabrics
Water supply
Railway transport
Water transport
Agriculture and forestry
Wood products
Furniture, jewerly and toys
Health, vetenary, social work
Air transport
Sewerage and sanitary services
Hotels and restaurants
Glass, ceramics, stone
Industrial products
Vehicles and ships
Machinery
Public admin and defence
Food processing
Telecommunications
Education
Pulp and paper
Metal products
Recreation
Rubber and plastic
Electricity
Gas distribution
Wholsale and retail
Land Transport
Coke, petroleum & nuclear
Construction
Banking and insurance
Electrical equipment
Coal, gas and mining
Postal and courier
Business services and real estate
0
0.25
0.5
0.75
1
Indirect economic loss £M/day(2009)

PART 3

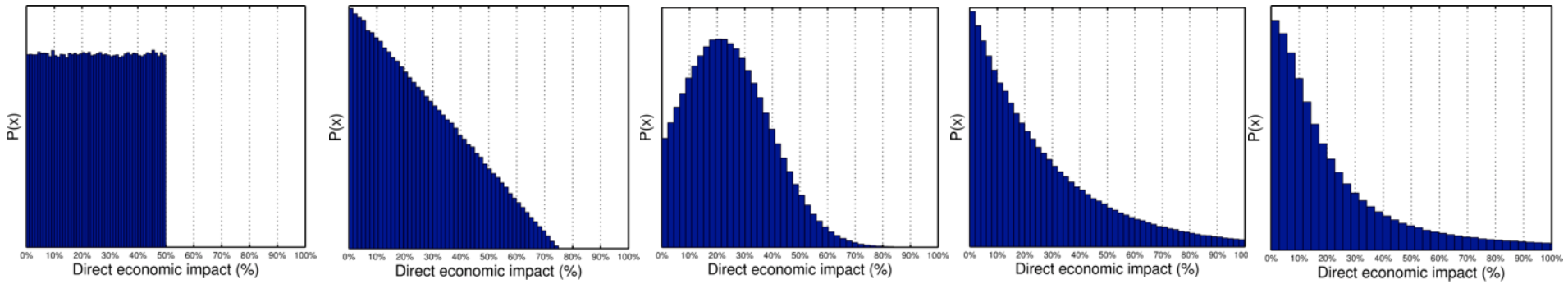
MonteCarlo Analysis

MonteCarlo analysis and Input Output

- How do prior probability distributions impact economic loss?
- Can our understanding of priors be used to understand infrastructure resilience?

Method

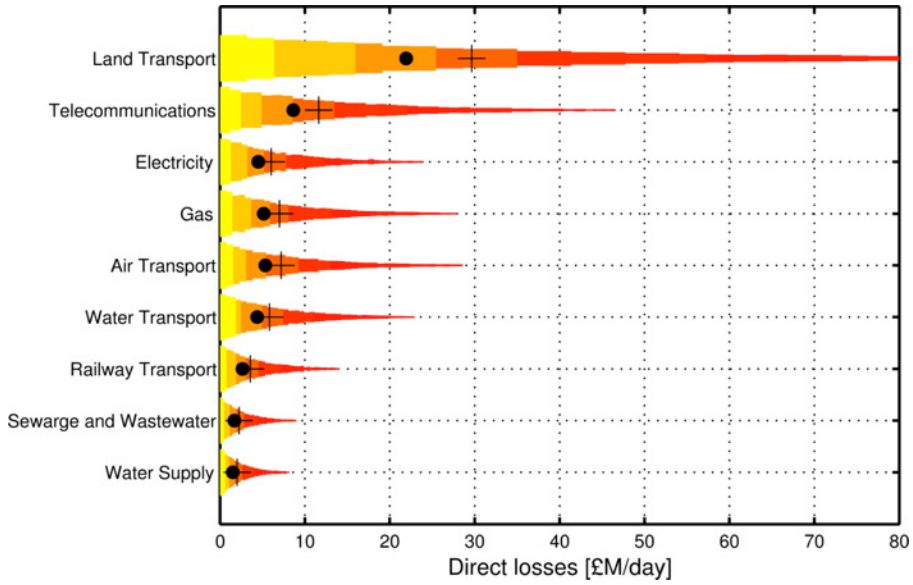
- Five unique probability distributions were created with samples of 1 million values.
- Each distribution has the same expected value E[x] = 0.25 (e.g. 25% failure)
- 10,000 sets of nine direct shocks were drawn from each distribution at random.



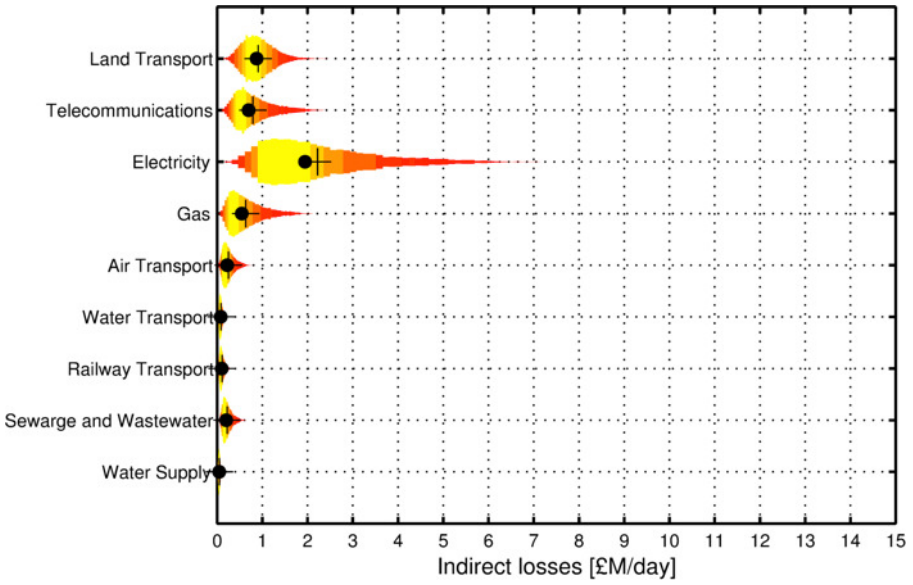
Uniform | Triangular | Normal | Lognormal | Cauchy

Direct and indirect losses (lognormal distribution)

Direct losses

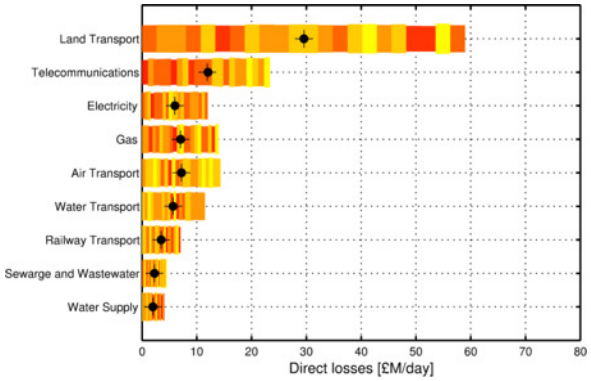


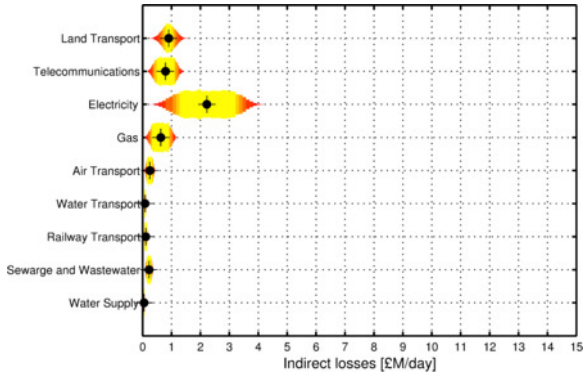
Indirect losses

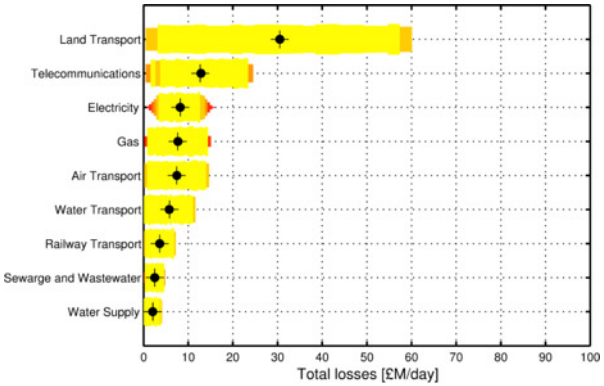


MonteCarlo simulations

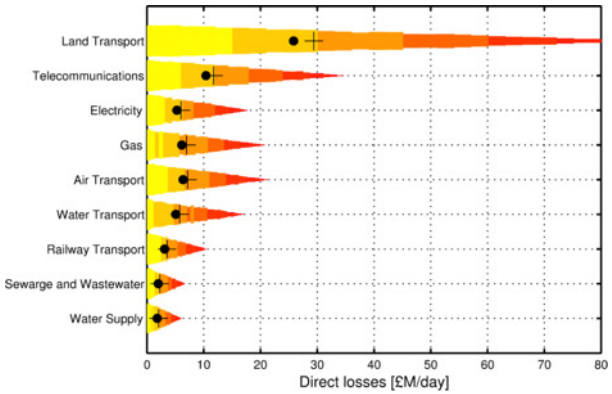
Uniform distribution

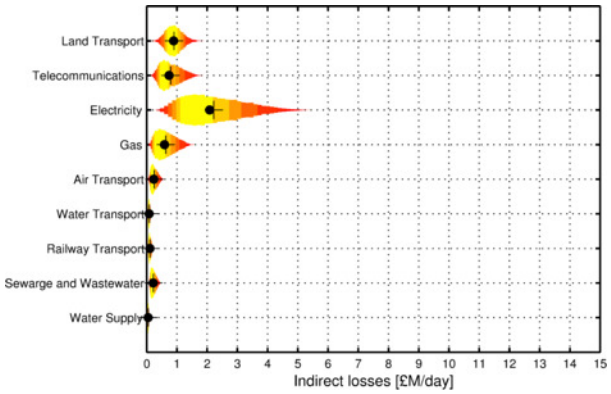


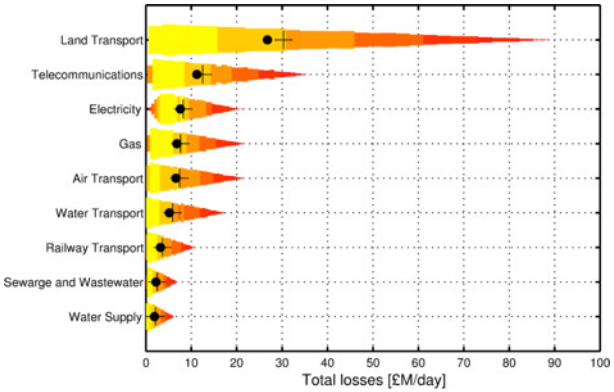




Triangular distribution

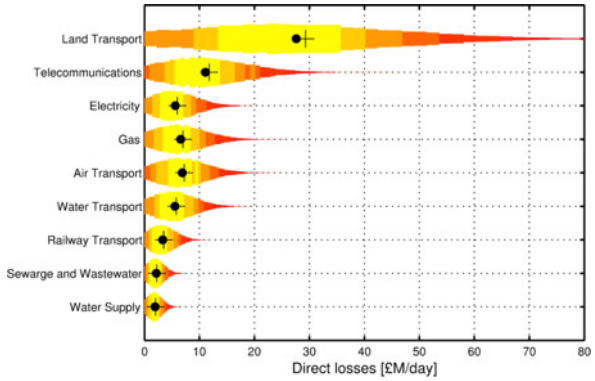


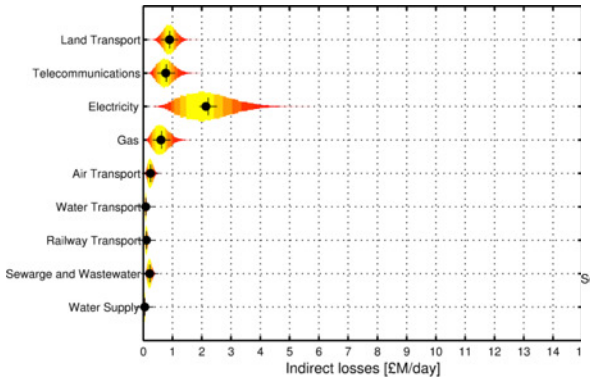


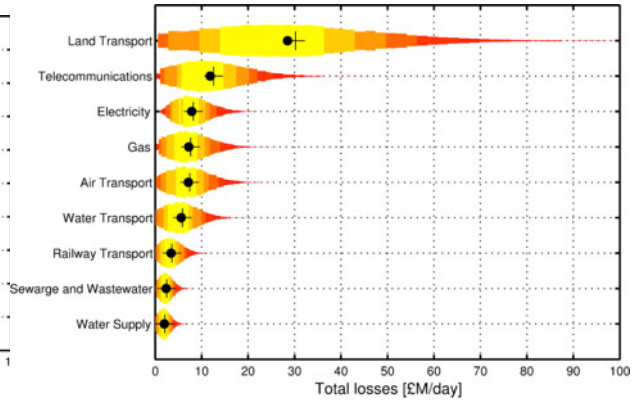


MonteCarlo simulations

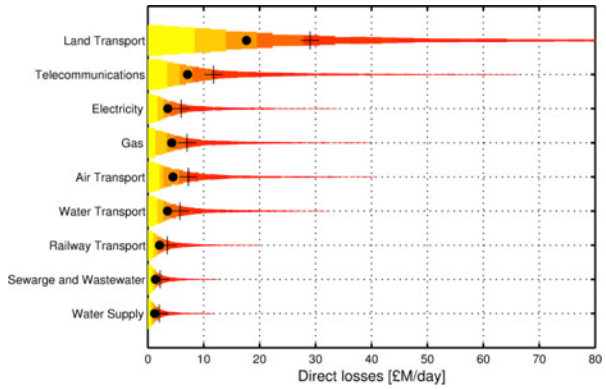
Normal distribution

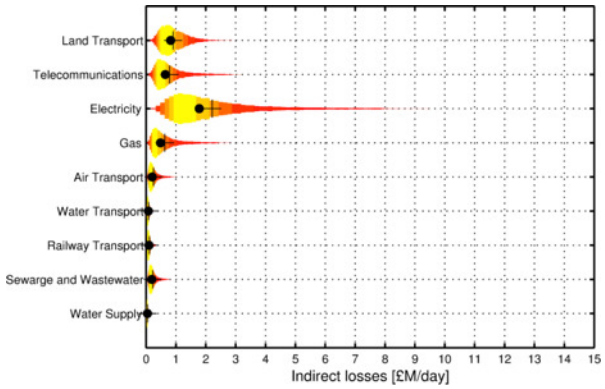


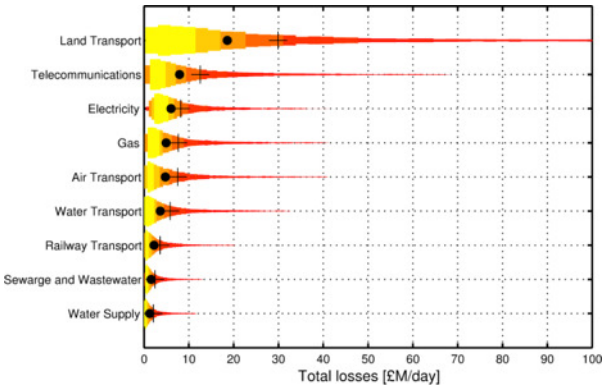




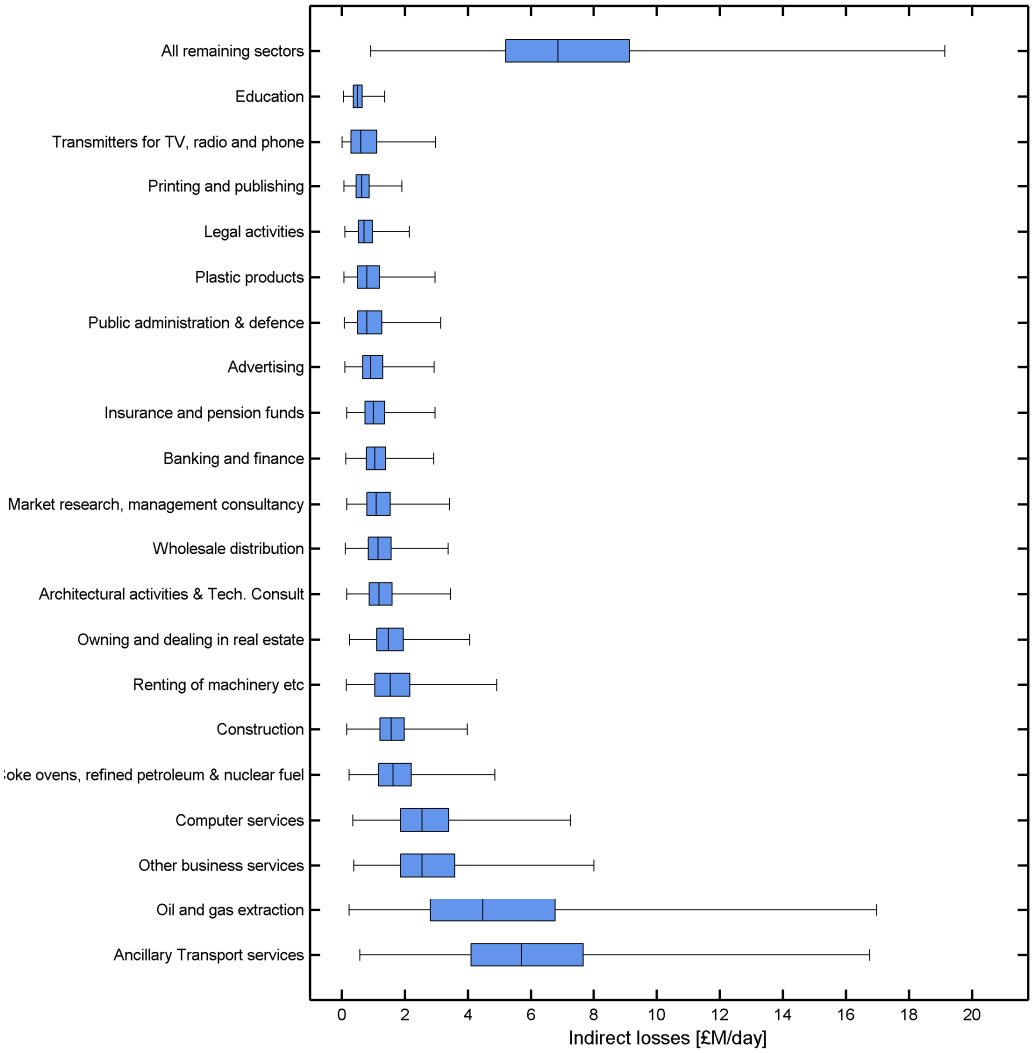
Cauchy distribution

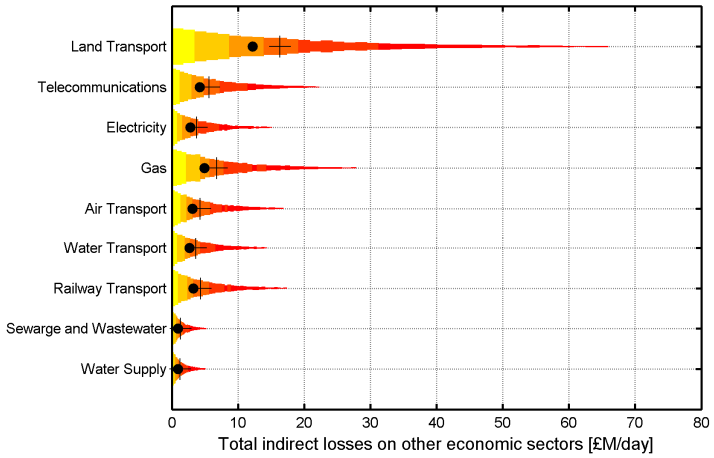






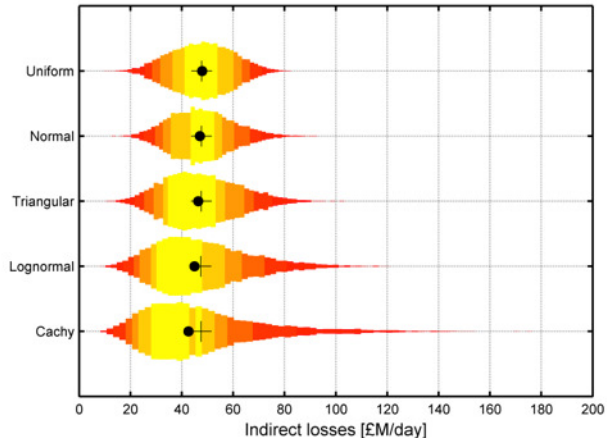
Indirect losses to non-infrastructure sectors

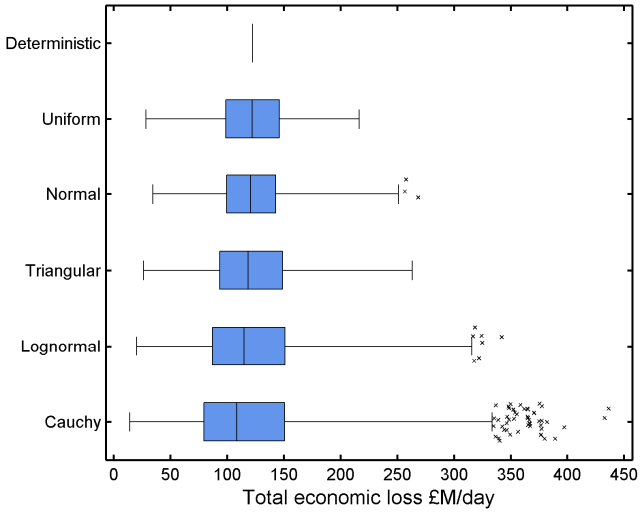




Indirect Losses	Median	Mean	95% Confidence Interval	
Land Transport	16.35	12.22	0.73	46.98
Telecommunications	5.66	4.23	0.20	16.10
Electricity	3.77	2.79	0.12	11.08
Gas	6.82	4.96	0.58	19.64
Air Transport	4.28	3.15	0.79	12.40
Water Transport	3.61	2.64	0.08	10.51
Railway Transport	4.37	3.26	0.18	12.62
Sewarge and Wastewater	1.29	0.96	0.01	3.70
Water Supply	1.26	0.92	0.06	3.68

Indirect and total losses for different distributions





Indirect Losses	Median	Mean	95% Confidence Interval	
Deterministic	47.60	47.60	47.60	47.60
Uniform	47.87	47.78	25.65	70.07
Normal	47.02	47.60	26.11	72.63
Triangular	46.30	47.66	23.11	77.88
Lognormal	44.63	47.60	19.47	88.56
Cauchy	42.82	47.37	16.83	107.53

Total Losses	Median	Mean	95% Confidence Interval	
Deterministic	122.5	122.5	122.5	122.50
Uniform	123.34	123.01	63.37	181.19
Normal	120.78	122.52	66.26	187.82
Triangular	118.4	122.65	57.45	204.84
Lognormal	114.23	122.52	49.08	237.93
Cauchy	108.85	121.91	41.69	283.92

Conclusions

- Infrastructure is a distinct form of capital
- The GVA contribution from infrastructure has been decreasing for several decades
- Infrastructure has both ‘physical’ and ‘economic’ connections
- ‘Hot Spot’ analysis estimates indirect losses of £0.75 M/day and total economic losses of £2.0 M/day
- We need better probabilistic modelling for estimating uncertainty in economic losses.

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Definitions infrastructure in IO tables

Electricity and distribution

- Generation, transmission, distribution
- Operation of facilities (nuclear, thermal, hydroelectric, gas, diesel, renewables)
- Sale of electricity to the final user and power brokers

Gas distribution

- Manufacture, transmission and distribution of gas
- Transportation, distribution and supply of gaseous fuels
- Steam and hot water supply

Water supply

- Collection, purification and distribution of water
- Desalination of sea water
- Excludes: irrigation, treatment of waste water for preventing pollution

Definitions infrastructure in IO tables

Sewerage and sanitary services

- Collection and treatment of sewerage and waste water
- Maintenance of sewer drains
- Collection of solid waste from business and households
- Collection and disposal of construction waste, oil and fuels, radioactive waste from hospitals and incineration.

Telecommunications

- Transmission of sounds, images, data and other information via cables, broadcasting, relay or satellite.
- Telephone, internet and radio.

Railway transport

- Passenger and passenger freight transport by inter-city rail services
- Excludes: maintenance and minor repair of rolling stock
- Excludes: urban and sub-urban transportation by underground, metro or similar

Definitions infrastructure in IO tables

Land transport

- Inter-urban transport of passengers on scheduled routes
- Urban and suburban passenger railway transportation by underground/metro
- Taxis; renting private cars and buses; freight transport; transport via pipelines.

Water transport

- Passenger and freight by sea, coastal and inland water transport

Air transport

- Transport of passengers or freight by air or via space
- Excludes: crop spraying, aerial advertising, overhaul of aircraft engines

What sectors linkages are important to infrastructure?

Backward linkages

Above average linkages:

(18) Electricity

(19) Gas Distribution

(22) Land Transport

(25) Railway Transport

Most important sectors to infrastructure:

(31) Business services and real estate

(30) Banking, finance, insurance

(9) Coke ovens, petroleum, nuclear

Forward linkages

Above average linkages:

(35) Sewerage and sanitary services

(29) Telecommunications

(25) Railway transport

(18) Gas distribution

(19) Electricity Production and distribution

Most important sectors to infrastructure:

(31) Business services and real estate

(23) Wholesale retail distribution

(38) Non-profit institutions serving households