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Projects as Interventions in Infrastructure Systems-of-Systems

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Projects as Interventions in SoSs

1. Infrastructure projects occur in the built environment SoS
2. Systems of Systems
3. Research priorities
4. An initial study with Thames Tideway
5. Concluding remarks

Built Environment

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Resilient cities
Cities

Newcastle's 'digital twin' to help city plan for disasters

Replica allows real-time testing of city's infrastructure in the face of emergencies – and in future could be used in cities worldwide

Cities is supported by The Rockefeller Foundation
About this content
Tom White
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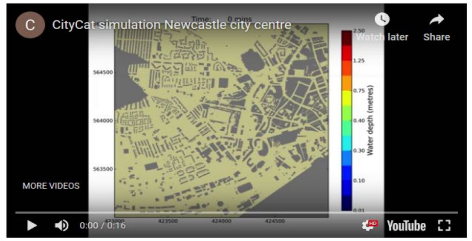

This video shows a simulation of flooding in Newcastle, but the 'digital twin' is even more sophisticated, allowing multiple variations.

In a world first, a new project aiming to create a computer replica of an entire city will allow experts to perform real-time resilience testing to see how its infrastructure will perform in the face of challenges such as climate change and population growth.

Known as a "digital twin", the technology is already used by Formula One teams and engine manufacturers like Rolls Royce, but its use on this scale is unprecedented. It is hoped that the technology will enable cities around the world to respond quickly and effectively to future threats such as rising sea levels, freak weather events, drought and energy shortages.

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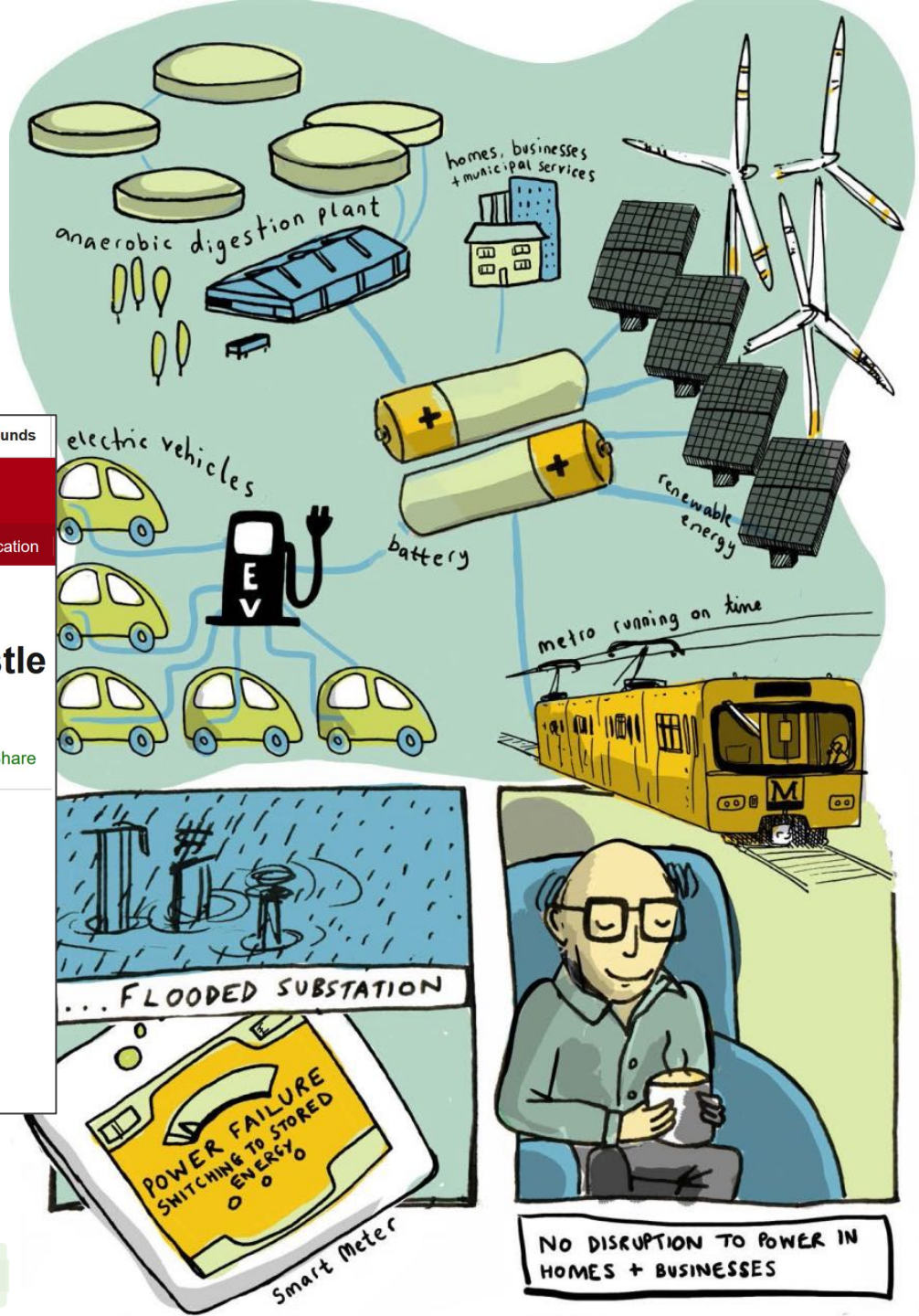
'Thunder Thursday' floods cost Newcastle Council £8m

25 July 2013 Share

Two hours of torrential rain in the North East dubbed "Thunder Thursday" caused £8m of damage to homes, roads and businesses, a report has found.

Newcastle City Council said 50mm of rain fell - a month's worth - on 28 June 2012 having a "devastating impact" and flooding 500 homes in the city.


Heavy rain causes disruption and local flooding in the North East.



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Projects as Interventions

"Schedule 1 of the Building Regulations 2010 … can lead to design and construction being seen as a set of siloed requirements, generally aligned with trades. This approach can lead to a situation where changes are made to one aspect of a building without sufficient consideration of the secondary effect (e.g. on fire safety). Instead the building must be considered as a single, coherent system."

Dame Judith Hackitt, *Building a Safer Future, 2018*

By ChiralJon - Grenfell Tower, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=60129791

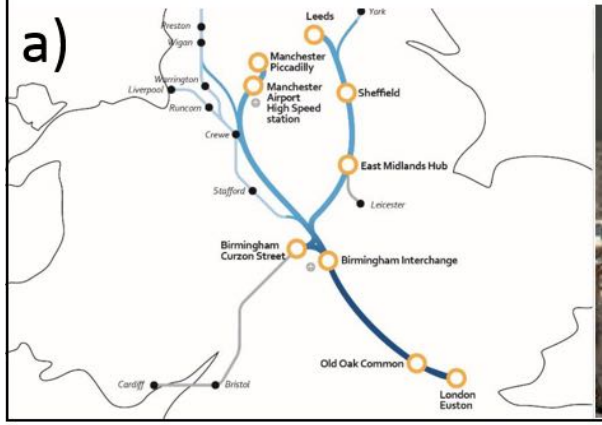
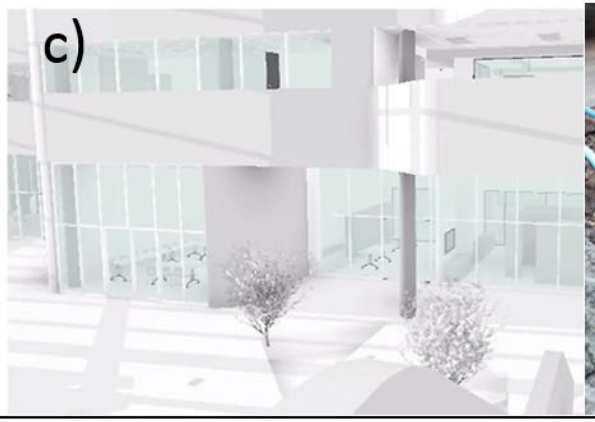
Projects as Interventions

- Construction sector significant: 8% of UK GDP, 10% of workforce
- Productivity and margins low
- Increasing tendency to view projects in the built environment in systems terms.
- These systems are open and interconnected, increasingly cyber-physical - requires the integration of computing and longer established engineering disciplines
- Paper suggests a research agenda on next-generation systems engineering methods and tools for infrastructure

Policy landscape interested in systems approaches

Projects as Interventions

Infrastructure involves highly interdependent transport, water, building, power and energy systems-of-systems – relation of the project and existing infrastructure changes across scales

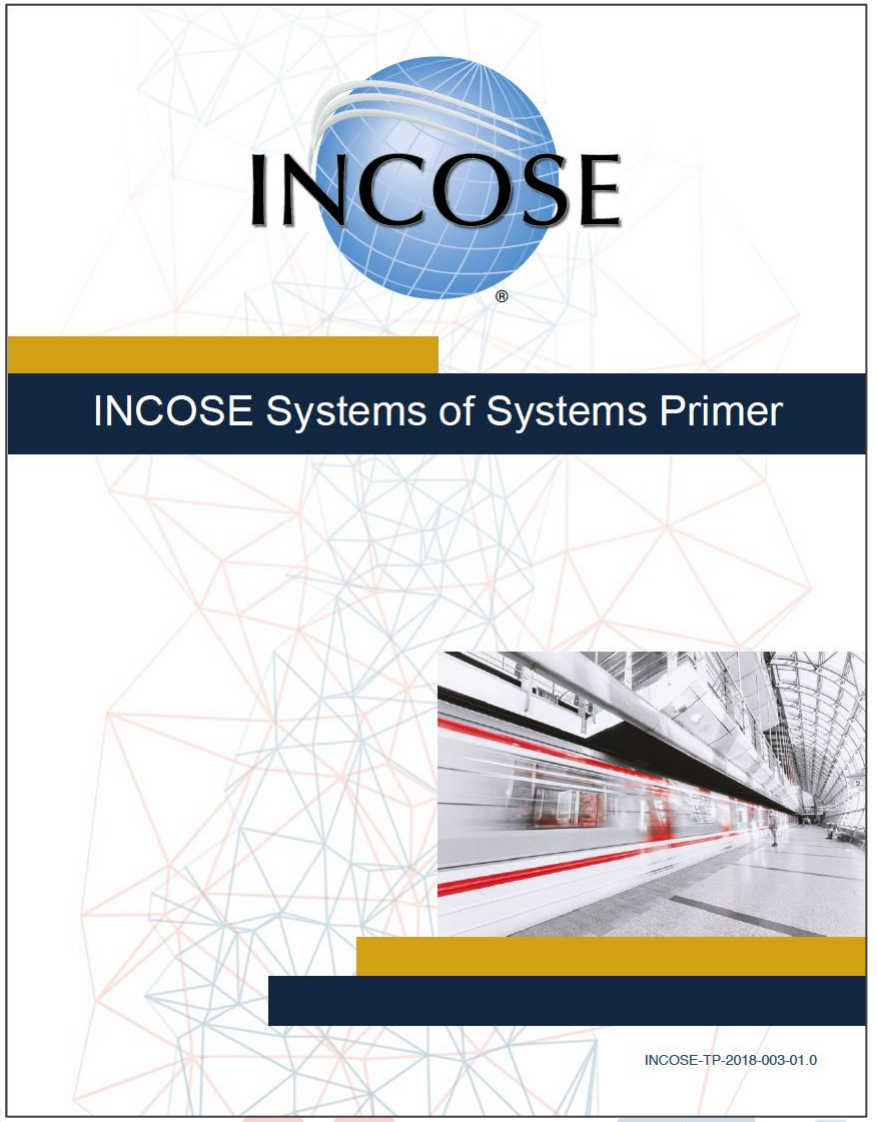
Large-scale (£10bn+) with multiple sets of projects as interventions	Large (£1-10bn) high internal complexity of projects / sub-projects	Project (£1-99m) most buildings and many infrastructure intervention	Portfolio of infrastructure interventions (under £1m)
a) 	b) 	c) 	d) 

Systems of Systems

A collection of independent systems, integrated into a larger system that delivers unique capabilities.

The independent constituent systems collaborate to produce global behaviour that they cannot produce alone.

- Operationally & managerially independent constituents
- Geographically distributed
- Continuously evolving
- Exhibiting emergent behaviour, on which reliance has come to be placed



SoS Pain Points

SoS Authority

What are effective collaboration patterns in SoS?

Leadership

What are the roles and characteristics of effective SoS leaders?

Capabilities & Requirements

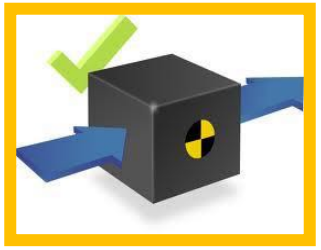
How can SE address SoS capabilities and requirements?

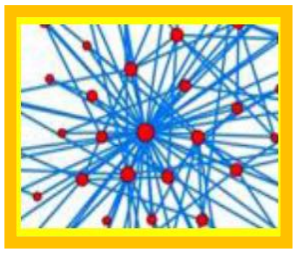
Constituent Systems

What are effective approaches to integrating constituent systems?

Testing, Validation & Learning

How can SE approach SoS validation, testing, and continuous learning in SoS?





Autonomy, Interdependencies & Emergence

How can SE address the complexities of interdependencies and emergent behaviors?

SoS Principles

What are the key SoS thinking principles?

Dahmann, Judith. (2014). System of Systems Pain Points. INCOSE Intl. Symp. 24.

Technical Challenges

Workshops and conversations with 11 companies:

- Owners/operators of infrastructure (Anglian Water, Network Rail)
- Architecture and engineering design consultants (Hawkins Brown, Arup, Mott Macdonald)
- Contractors (Laing O'Rourke),
- Digital software and systems providers (Bentley Systems, Siemens)
- Manufacturers (Rolls Royce), and major projects (HS2, Tideway).

Messages:

1. There is not the time in project delivery to undertake comprehensive analyses that may need years.
2. There is increasing complexity, as infrastructure SoS become cyber-physical, dependent on computing as well as more traditional engineering disciplines.
3. There may be emergent properties across scales.

Technical Challenges

1. Generate results in time for engineers to use them in decisions on infrastructure projects.
2. Integrate different types of models to address the cyber-physical nature of infrastructure.
3. Model across scales to address the interconnected nature of infrastructure.

New techniques are needed to automate aspects of SoSE to provide rapid insights into interdependencies.

As infrastructure SoS control/monitoring becomes more algorithmic, design of interventions requires new forms of analysis and model integration, for better understanding of operations in design stages.

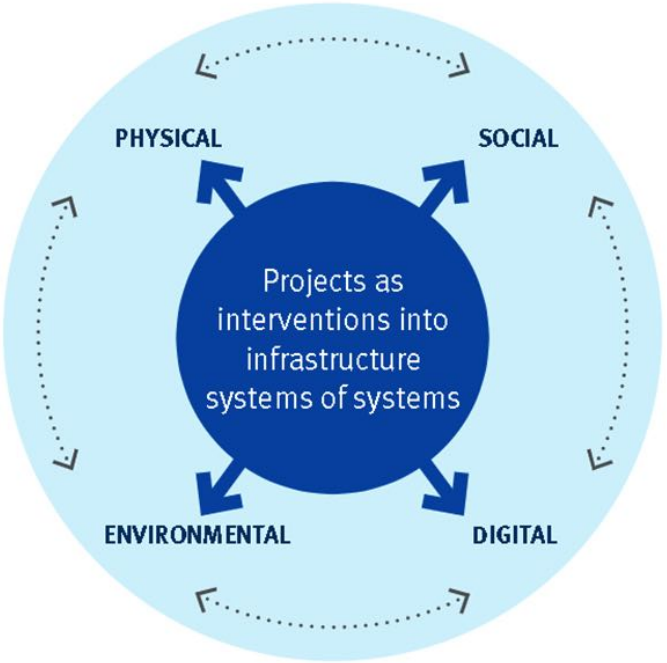
Multiple interdependencies across CS boundaries lead to SoS behaviours that are not well understood (owned?) in existing tools and methods.

Research Agenda

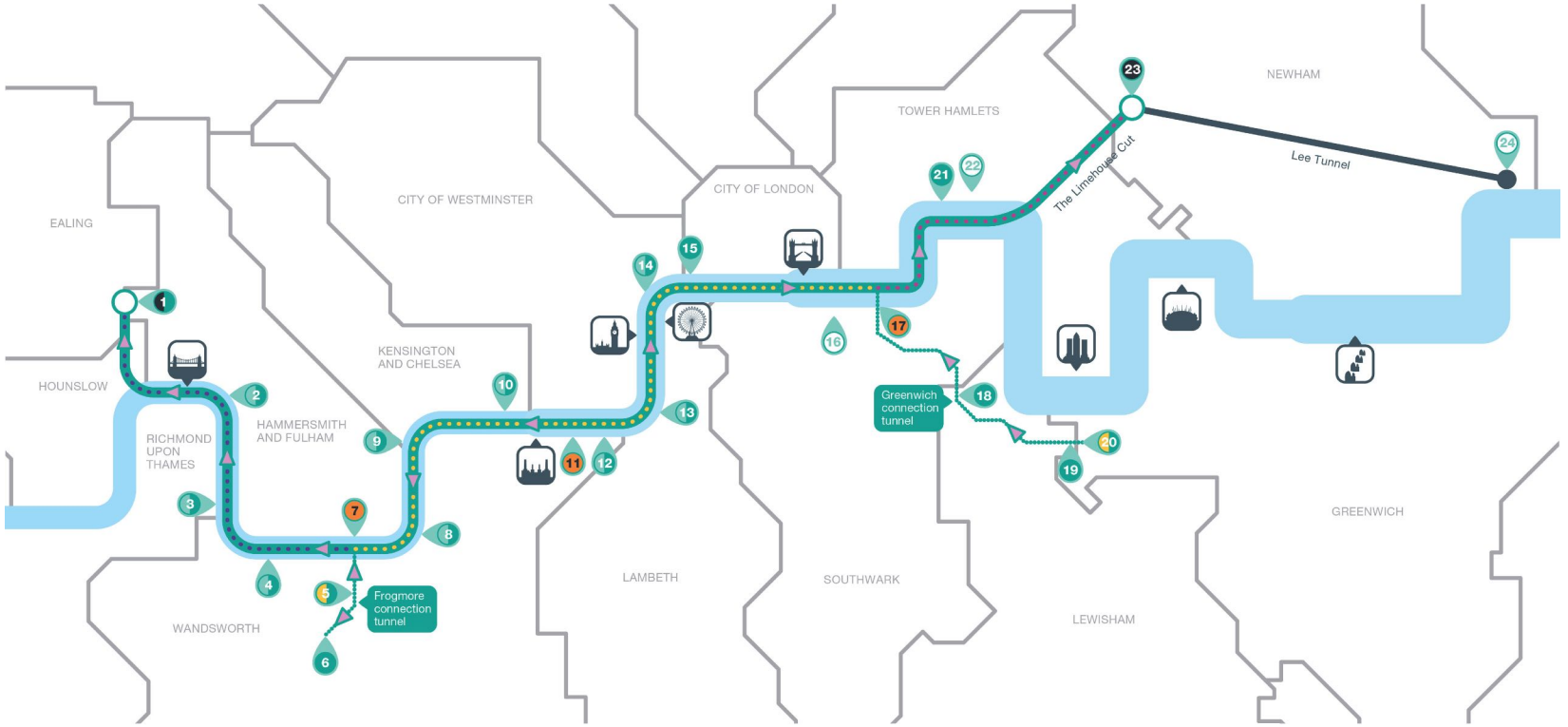
1. Connect models to provide systemic understanding

2. Support decision-making in multidisciplinary infrastructure design through rapid analyses

3. Manage uncertainty and enabling traceability in infrastructure design



A Study with Thames Tideway



Map key

- Main tunnel drive site
- Main tunnel reception site
- CSO site
- Short connection tunnel drive site
- Long connection tunnel drive site
- System modifications
- Main tunnel
- Long connection tunnel
- Lee Tunnel (under construction)
- Proposed drive direction
- West works site
- Central works sites
- East works site

1. Acton Storm Tanks
2. Hammersmith Pumping Station
3. Barn Elms
4. Putney Embankment Foreshore
5. Dormay Street
6. King George's Park
7. Carnwath Road Riverside
8. Falconbrook Pumping Station
9. Cremorne Wharf Depot
10. Chelsea Embankment Foreshore
11. Kirtling Street
12. Heathwall Pumping Station
13. Albert Embankment Foreshore
14. Victoria Embankment Foreshore
15. Blackfriars Bridge Foreshore
16. Shad Thames Pumping Station
17. Chambers Wharf
18. Earl Pumping Station
19. Deptford Church Street
20. Greenwich Pumping Station
21. King Edward Memorial Park Foreshore
22. Bekesbourne Street
23. Abbey Mills Pumping Station
24. Beckton Sewage Treatment Works

- £3bn project to deliver a major new sewer through the center of London
- Built to protect the river Thames from pollution
- Project crosses/touches water mains, bridges, river walls, 24 listed (protected) buildings, 1301 buildings, other services and tunnels.

Analysing Interdependencies

A host of analytic techniques and tools …

System Dynamics	BIM Query Supported DSM	Linked Data	Multi-modelling
GIS System	Simulation	Network Theory	...

Analysing Interdependencies

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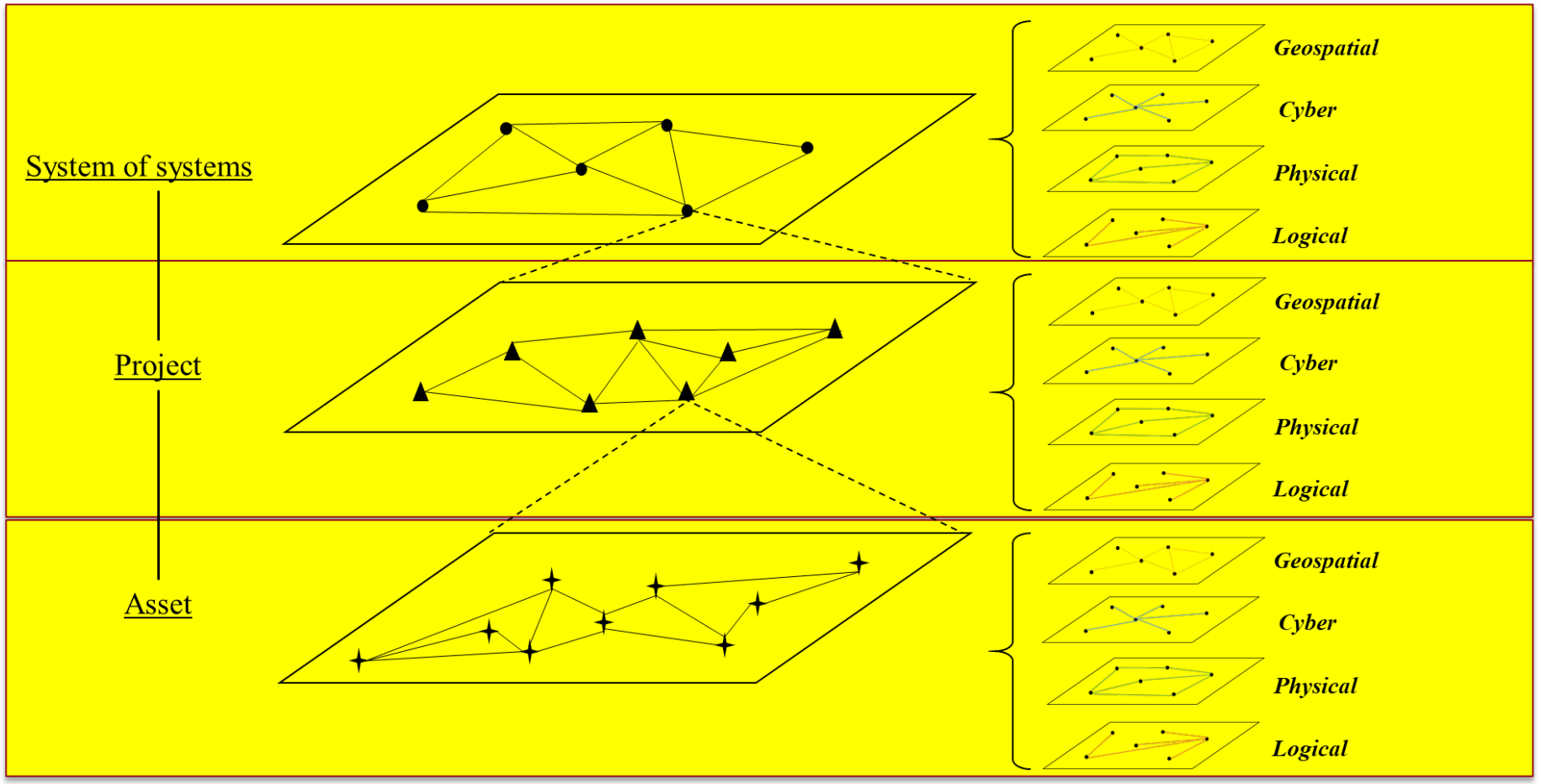
Analysing Interdependencies



Network Theory

Multi-modelling

BIM Query Supported DSM

Towards Guidance …

BIM Query

Su

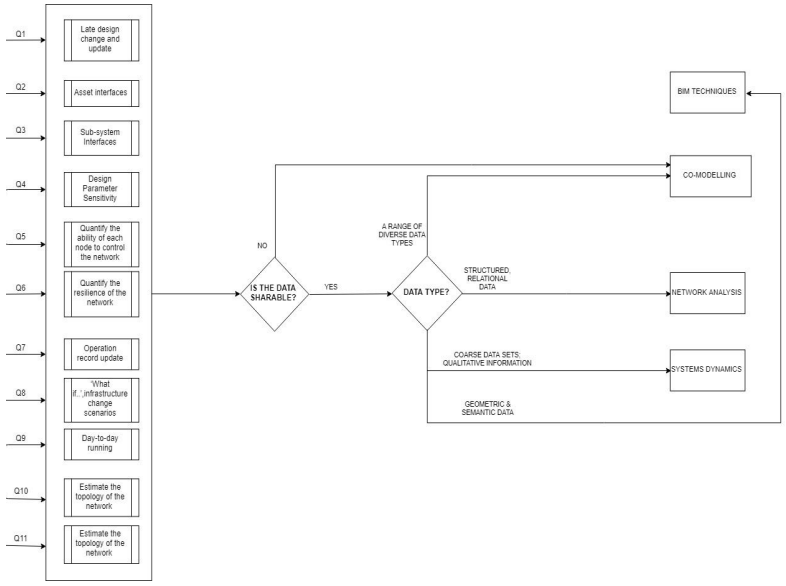
m

Network Theory

Modelling Approaches

Example questions in design/delivery
1. What are the system consequences of a late design change?
2. What are the operational consequences of asset interdependencies?
… …
Example questions in operations
6. How robust is my network design to node failures?
7. How to manage the facilities according to updated operation record?
… …

Problems & Use Cases



Decision-Tree

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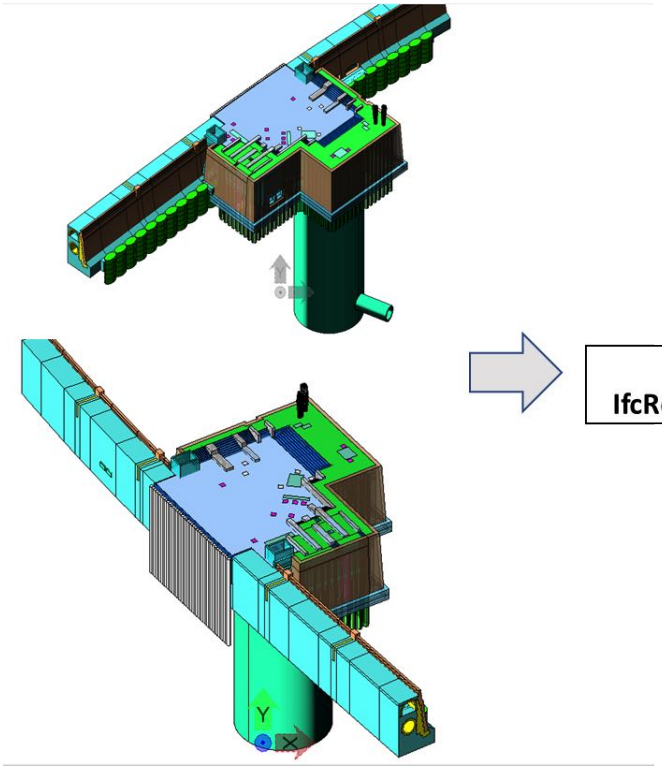
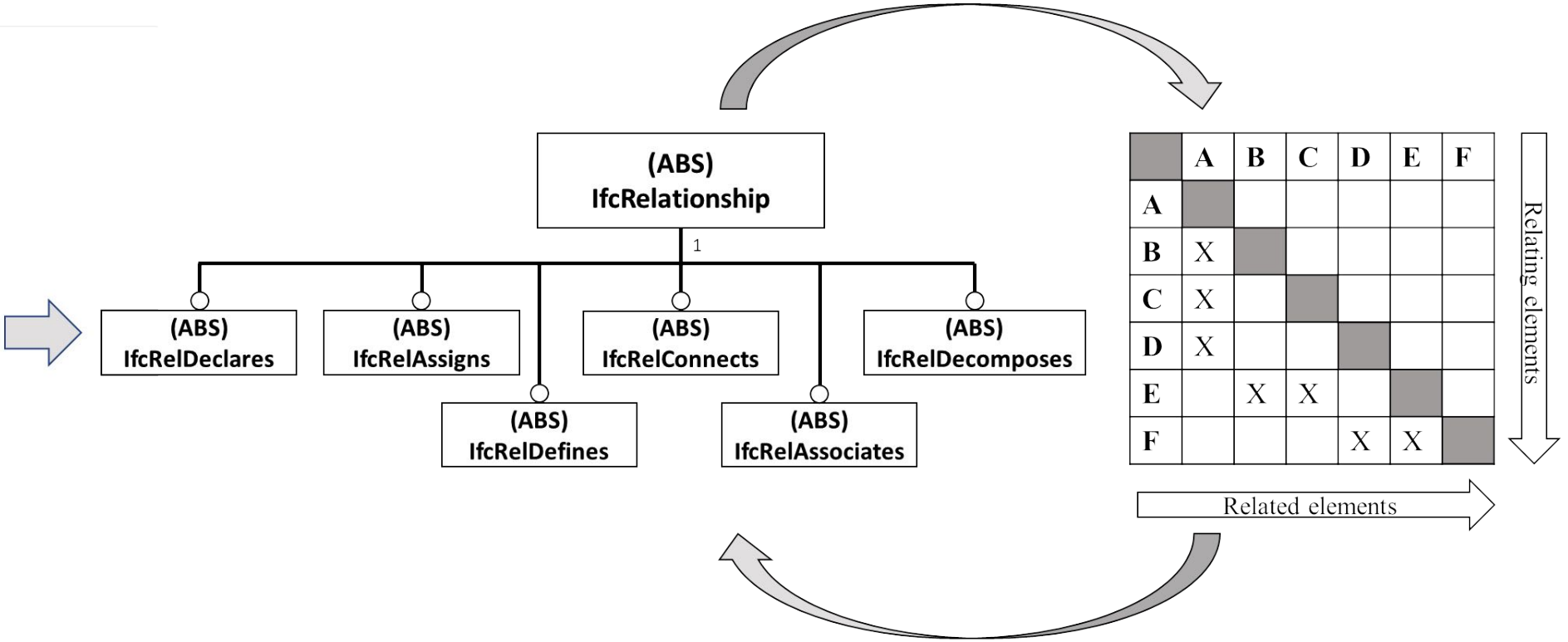
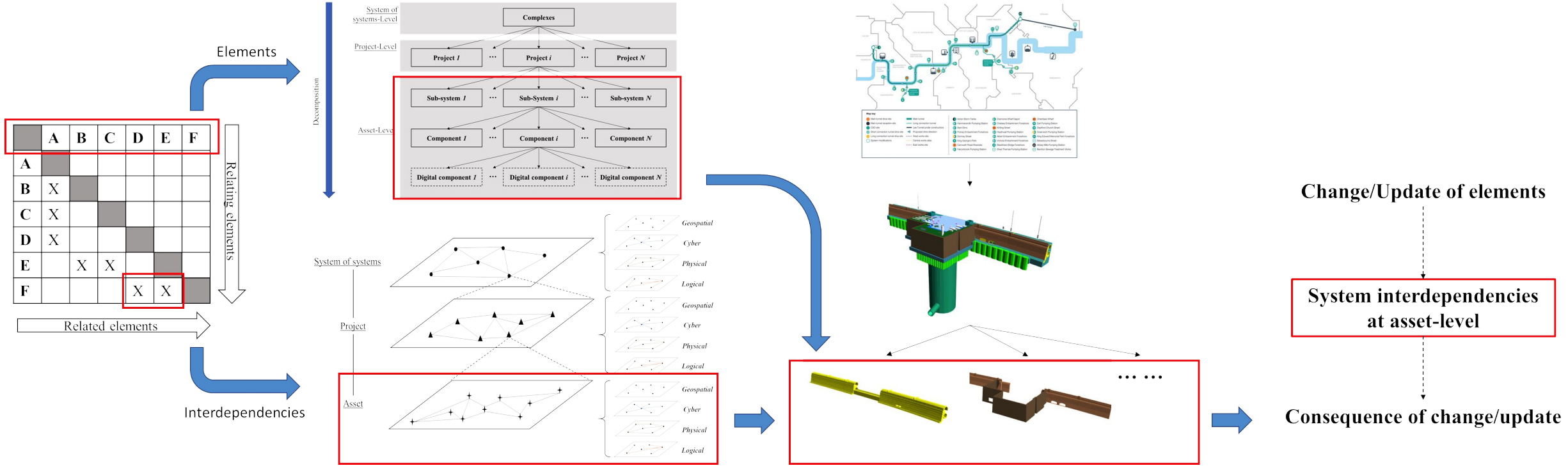
BIM Query Supported DSM





BIM Query Supported DSM

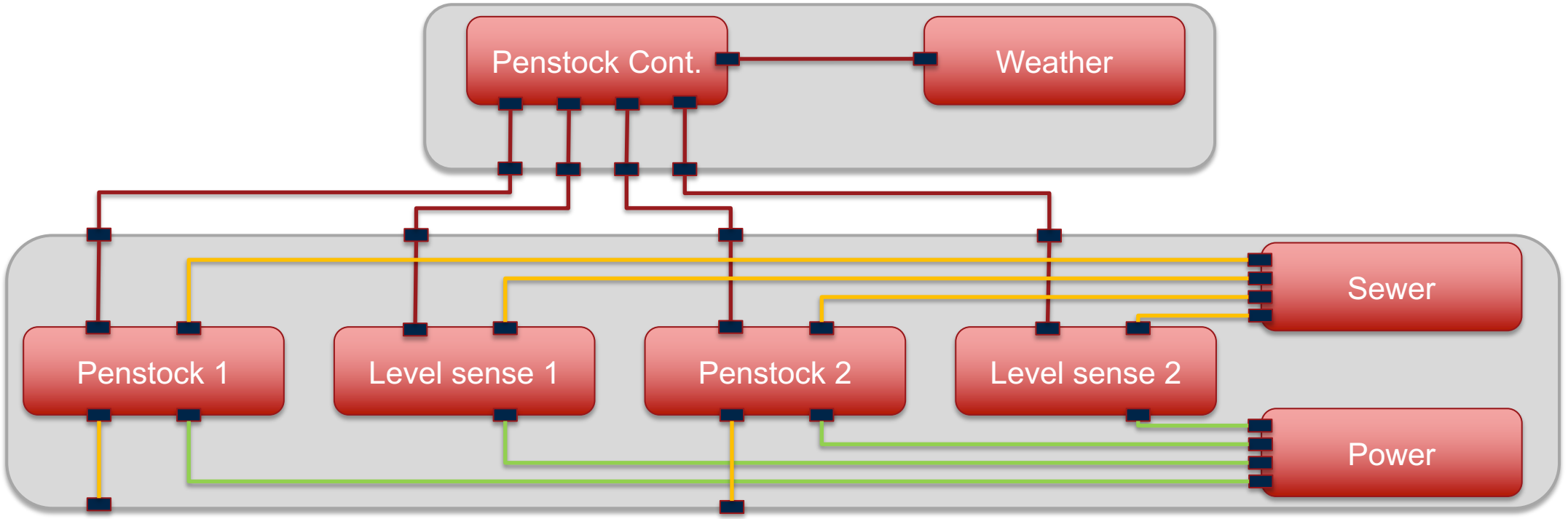
Design-Q1: How do you understand the system consequences of a late design change?
Operation-Q7: How to manage the facilities according to updated operation record?



(Image source: http://ukwaterprojects.com/case_studies/2016/online/thames_tideway_east_2016.htm)

Multi-Modelling

Design-Q2 What are the operational consequences of asset interdependencies?
Design-Q3 What are the interdependencies between the assets developed in the project and the wider infrastructure network?



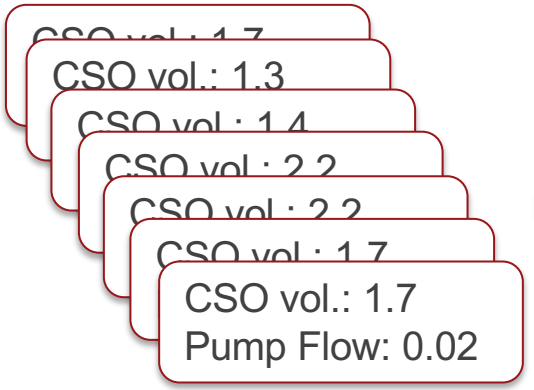
Multi-Modelling

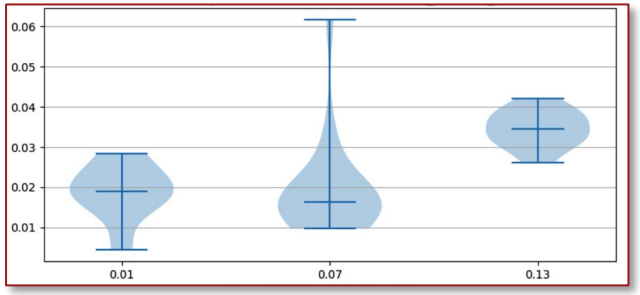
Design-Q4 Which are the critical parameters in the design?

Makes use of optimisation engine (DSE) to explore effect of changing parameters

Sweep parameters → *Simulation results* → *Objective results* → *Parameter effect*

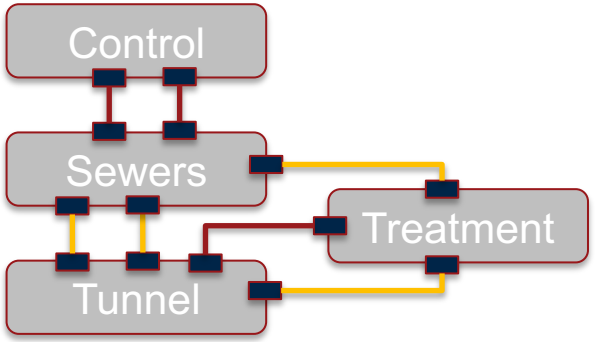
Open level: <a1...an>
Close level: <b1...bn>
Opening Speed: <c1...cn>
Penstock width: <d1..dn>





Multi-Modelling

Operation-Q8 What is the effect on system behaviour of changing network topology or node properties?
Operation-Q9 How will the system behave given a set of environmental conditions?



Choice of FMU to suit analysis needs

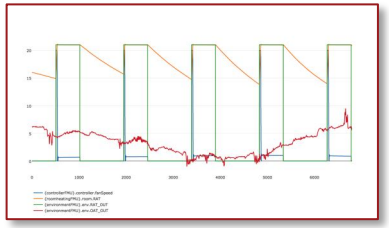
Significant changes to topology or properties

- Explicit, physical principle or computing model based FMUs
- Created by experts
- Results from understood mechanisms
- Potentially computationally expensive e.g. finite element fluid dynamics

Day-to-day running, variations on environmental conditions

- Machine learned FMUs
- Generated from recorded data
- Computationally less expensive after the learning process, e.g. system identification

Same analysis available



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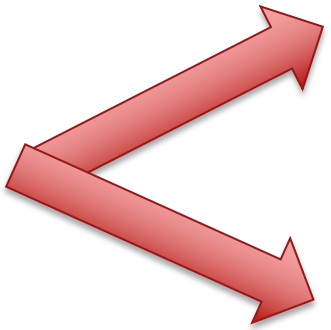
Pump Flow: 0.02

Network Theory

is the study of graphs as a representation of relations between discrete objects.

Applications of network theory in the MBSE for Infrastructure SoS

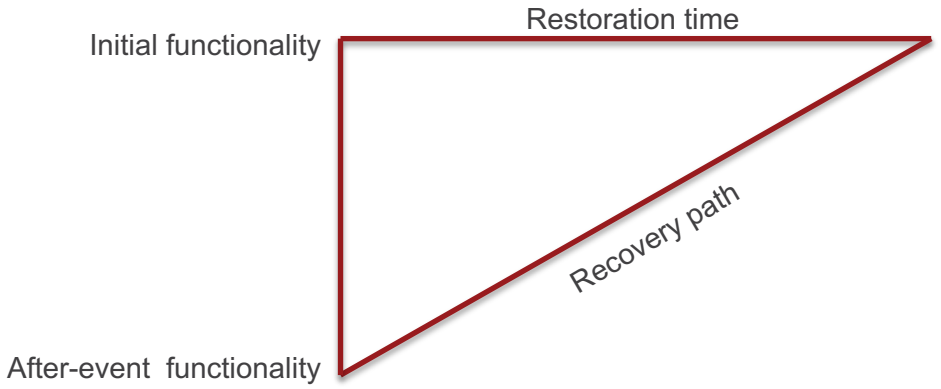


- Network topology optimization (to maximize controllability and resilience)
- Network identification (to estimate the topology of the network based on sensor data)

Network Theory

Q6: How robust is my network design to node failures?

- Quantify the resilience of a complex network
- Resilience: the ability to absorb disturbance and still retain basic functions and structural capacity
  - **Percolation theory:** assess the impact of removing a node or an edge from an interconnected network – network failure process
  - **Resilience measures:** resilience triangle

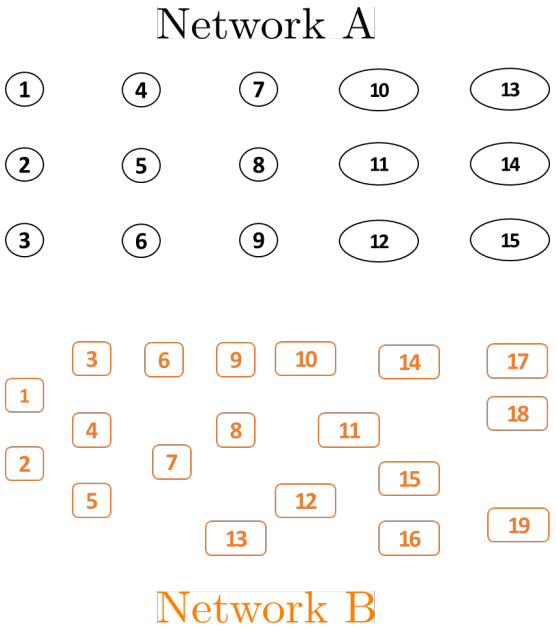


Resilience metrics	
Rapidity	Recovery speed after an event
Resilience loss	Area of the triangle
Resilience index	Relative lost functionality

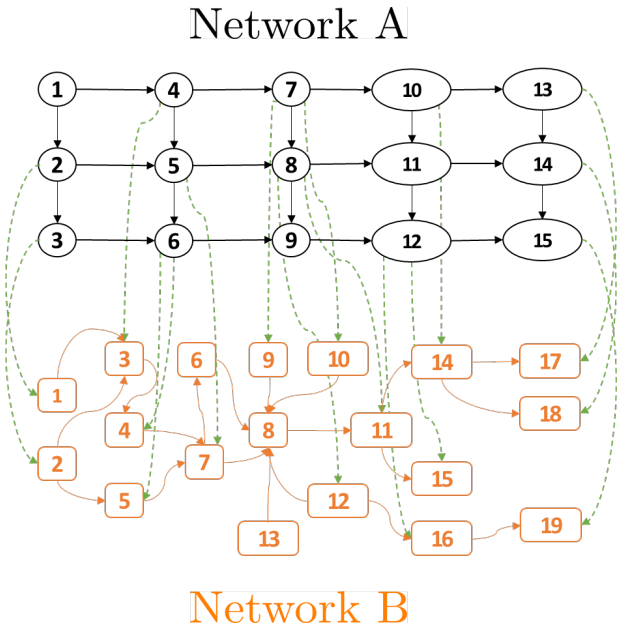
Network Theory

Q10b: What are the interdependencies between my network and other infrastructure systems?

Network identification for detecting interdependencies



Time series data in each node

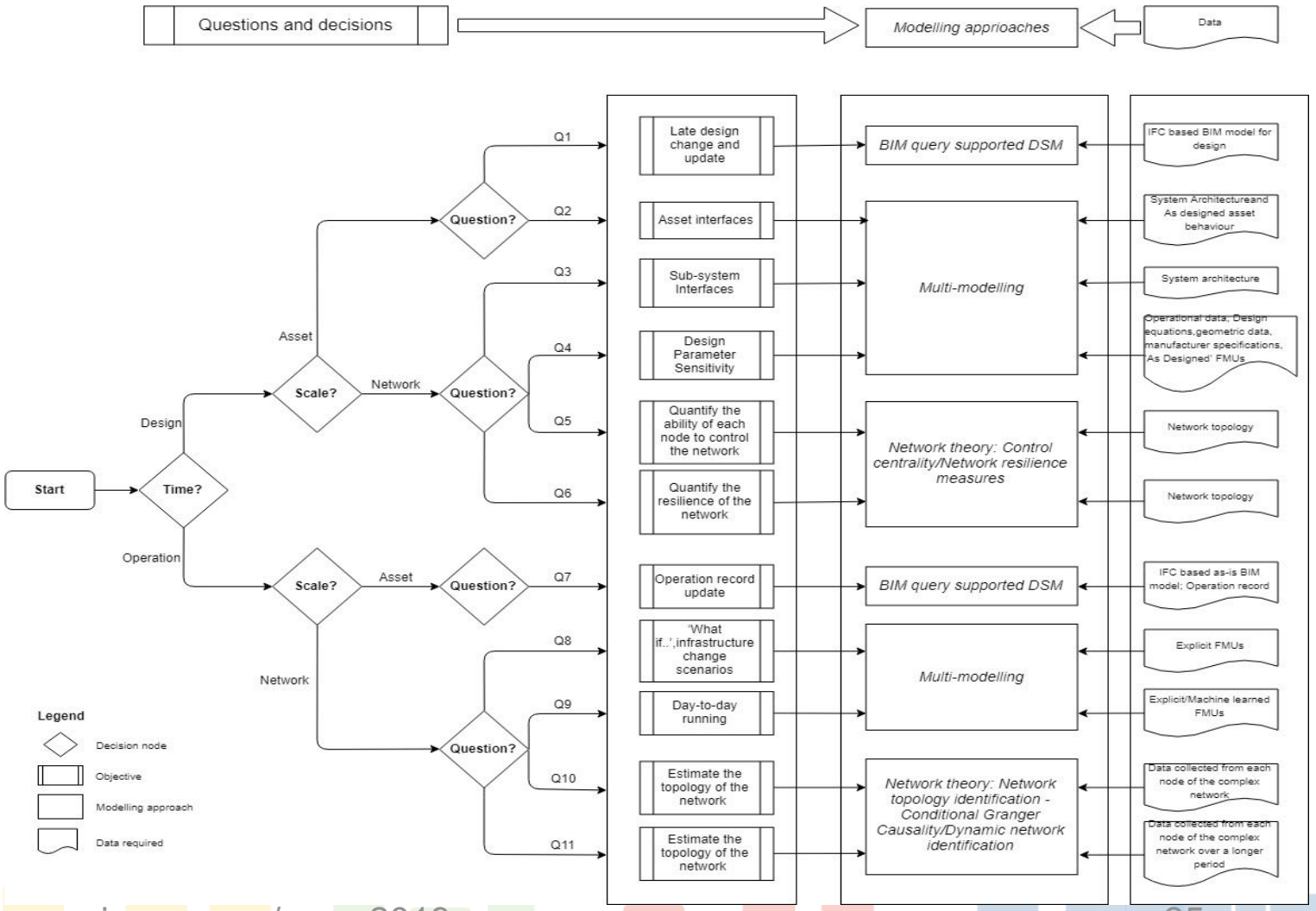


Practice Guides for SE in Infrastructure SoSs?

Practical guide to modelling and simulation approaches

- Design / operation?
- Asset or network views of the system?
- Use case?

- Different approaches for geometric / geometric and temporal data



Conclusions

- This is less SoS Engineering than doing SE in SoSs.
- We set out research on next-generation SE for infrastructure in SoSs:
  - Connect models to provide systemic understanding
  - Support decision-making in multidisciplinary infrastructure design through rapid analyses
  - Manage uncertainty and enabling traceability in infrastructure design
- Proposing how the use of digital data and analytics can enable engineering decision-makers to understand interdependencies
- Develop next-generation systems engineering tools and methods, to improve the productivity of infrastructure projects and their impact on the resilience of wider infrastructure systems-of-systems.
- What does this say for the competencies needed in the infrastructure engineering professions?

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