Massive Open Online Course
Resilience, Sustainability & Digitalisation in Critical Infrastructure

Lecture 6 Optimisation of resilience and sustainability

Lecture Notes

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Introduction

A Massive Open Online Course (MOOC) is a free, open, online course designed to offer a taste of higher education to learners from across the world. The University of Birmingham is delivering new MOOCs in partnership with FutureLearn. Delivered by world-class academics from the University of Birmingham and other partners of the HORIZON Recharged project (GA no. 101086413), the course enable learners worldwide to sample high-quality academic content via an interactive web-based platform from leading global universities, increasing access to higher education for a whole new cohort of learners.
The course is developed by senior academic staff and their content is reviewed regularly, taking into account student feedback.

This MOOC brings together world experts, including general audiences, aiming to provide training with life-long updates and professional development opportunities for general and specialised audiences. The MOOC contains all the necessary components of a university taught module, e.g. prerequisites, content and aims, learning outcomes, attributes for sustainable professional development (cognitive, analytical, transferable skills, professional and practical skills), expected hours of study, assessment patterns, units of assessment and reading list, warm-up sessions, with relevant podcasts and videos, lecture notes and recorded lectures, some of which will be tailored for general audiences. This open course will be available on futurelearn.com and on the project website.

These lecture notes are accompanying the seven lectures of the MOOC. Following is the MOOC description, which contains the outcomes, the aims per week and the learning activities. The latter include a combination of material acquisitions and discussions, investigations and production, practical examples and analysis of case studies, and a set of collaboration and discussion forum.

Outcomes

<u>Lecture 6-Week 6</u>
The aim of this week is to introduce optimisation of resilience and sustainability for critical infrastructure, including Multi-Criteria Decision-Making (MCDA) and Pareto fronts, in infrastructure management. Optimization paths will be used, revealing trade-offs and Monte Carlo approaches will be taught to enhance precision. Social factors in holistic decision-making will be introduced. A case study will be illustrated to understand how optimizing a critical climate-sensitive infrastructure underscores the synergy between MCDA, Pareto fronts, and Monte Carlo simulations, yielding robust solutions that balance environmental, economic, and social dimensions.

- Define common methods of optimisation and trade-offs (e.g. MCDA/Pareto) in infrastructure management.
- Present Monte Carlo optimisation approaches.
- Account for social impacts and participatory decision making towards optimised solutions.
- Present a case study on optimising resilience and sustainability of a critical infrastructure in climate change environment.

Lecture 6. Optimisation of resilience and sustainability

Lecture 6
Massive Open Online Course
Resilience, Sustainability & Digitalisation in Critical Infrastructure

Optimisation of resilience and sustainability

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Lecture 6 Outcomes

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Activity 1. Methods of optimisation /trade-offs in infrastructure management

ACTIVITY 1: Methods of optimisation / trade-offs in infrastructure management

- MCDA and Pareto front approaches
- Monte Carlo optimisation approaches
- Examples

Multiobjective optimisation (e.g., MCDA, vector and Pareto front)

Multiobjective optimisation is an area of multiple criteria decision making that is concerned with mathematical optimisation problems involving more than one objective function to be optimised simultaneously.

Most real-world engineering optimization problems are multi-objective in nature.

Objectives are often conflicting:

Resielience vs. Sustainability metrics

Capacity vs. Cost

Efficiency vs. Resilience etc

--The notion of "optimum" has to be redefined.

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Resilience vs. Sustainability metrics

Capacity vs. Cost
Efficiency vs. Resilience etc.
The notion of "optimum" has to be redefined.

Multiobjective optimisation (e.g., MCDA, vector and Pareto front)

- **Find a vector of decision variables** which satisfies constraints and optimises a vector function whose elements represent the objective functions.
- **Objectives might be in conflict with each other (typically they are)**
- **Optimise:** finding solutions which would give the values of all the objective functions acceptable to the designer/decision maker

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Multiobjective optimisation (e.g., MCDA, vector and Pareto front)

Mathematical formulation

Find the vector

$$\bar{x}^* = \left[x_1^*, x_2^*, \ldots, x_n^*\right]^T$$

Which will satisfy the *m* inequality constraints

$$g_i(\bar{x}) \geq 0 \quad i = 1,2,\ldots,m$$

The *p* equality constraints

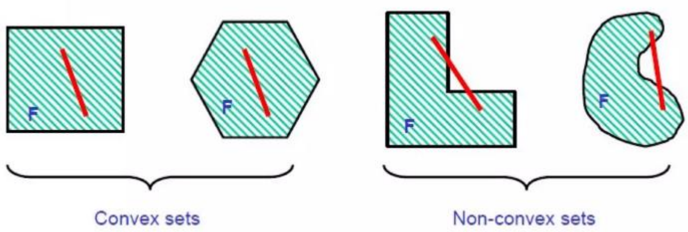
$$h_i(\bar{x}) = 0 \quad i = 1,2,\ldots,p$$

And optimizes the vector function

$$\bar{f}(\bar{x}) = \left[f_1(\bar{x}), f_2(\bar{x}), \ldots, f_k(\bar{x})\right]^T$$

Feasible region

$$\left.\begin{array}{ll} g_i(\bar{x}) \geq 0 & i = 1,2,\ldots,m \\ h_i(\bar{x}) = 0 & i = 1,2,\ldots,p \end{array}\right\} \text{Define the } \textit{feasible region } F$$



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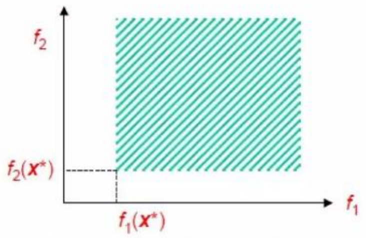
Multiobjective optimisation (e.g., MCDA, vector and Pareto front)

Meaning of optimum

We rarely have an **x*** such that

$$f_i\left(\bar{x}^*\right) \leq f_i\left(\bar{x}\right) \quad \forall\, \bar{x} \in F, i = 1,2,\ldots,k$$



We have to estabilish a certain criteria to determine what would be considered as an optimal solution

Multiobjective optimisation (e.g., MCDA, vector and Pareto front)

Monte Carlo optimisation approaches

A Monte Carlo simulation is a way to model the probability of different outcomes in a process that cannot easily be predicted due to the intervention of random variables. It is a technique used to understand the impact of risk and uncertainty.

Statistical simulation technique that provides approximate solution to problems expressed mathematically.

It utilize the sequence of random number to perform the simulation.

Furnishes the decision-maker with a range of possible outcomes and the probabilities that will occur for any choice of action.

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Multiobjective optimisation (e.g., MCDA, vector and Pareto front)

Monte Carlo optimisation approaches

- To understand this technique this is break down in 5 steps.

1. Establishing probability Distribution
2. Cumulative probability Distribution
3. Setting random number Intervals
4. Generating Random number
5. To find the answer of question asked using the above four step.

$$\text{Probability} = \frac{\text{Favourable Outcome}}{\text{Total Outcomes}}$$

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Example:

We have a coastal city with several bridges vulnerable to climate change impacts like sea-level rise and storms. The city wants to enhance the resilience of these bridges while balancing multiple objectives:

Minimizing Costs: Reducing the overall cost of adaptation (e.g., retrofitting, rebuilding, or relocating bridges).

Maximizing Resilience: Ensuring bridges can withstand future climate impacts.

Minimizing Environmental Impact: Reducing the ecological footprint of adaptation efforts.

Optimizing Social Impact: Maintaining accessibility and minimizing disruptions to local communities.

Monte Carlo Simulation Approach

Step 1: Define the Uncertainties

For each objective (cost, resilience, environmental impact, social impact), there are uncertainties related to future climate scenarios, material costs, technological effectiveness, and community responses. We assign probability distributions to these uncertainties:

Cost: Distribution based on estimates of material and labor costs.

Resilience: Distribution based on predicted climate impacts and the effectiveness of different adaptation measures.

Environmental Impact: Distribution based on the ecological effects of various construction methods.

Social Impact: Distribution based on potential disruptions and community responses.

Step 2: Generate Random Samples

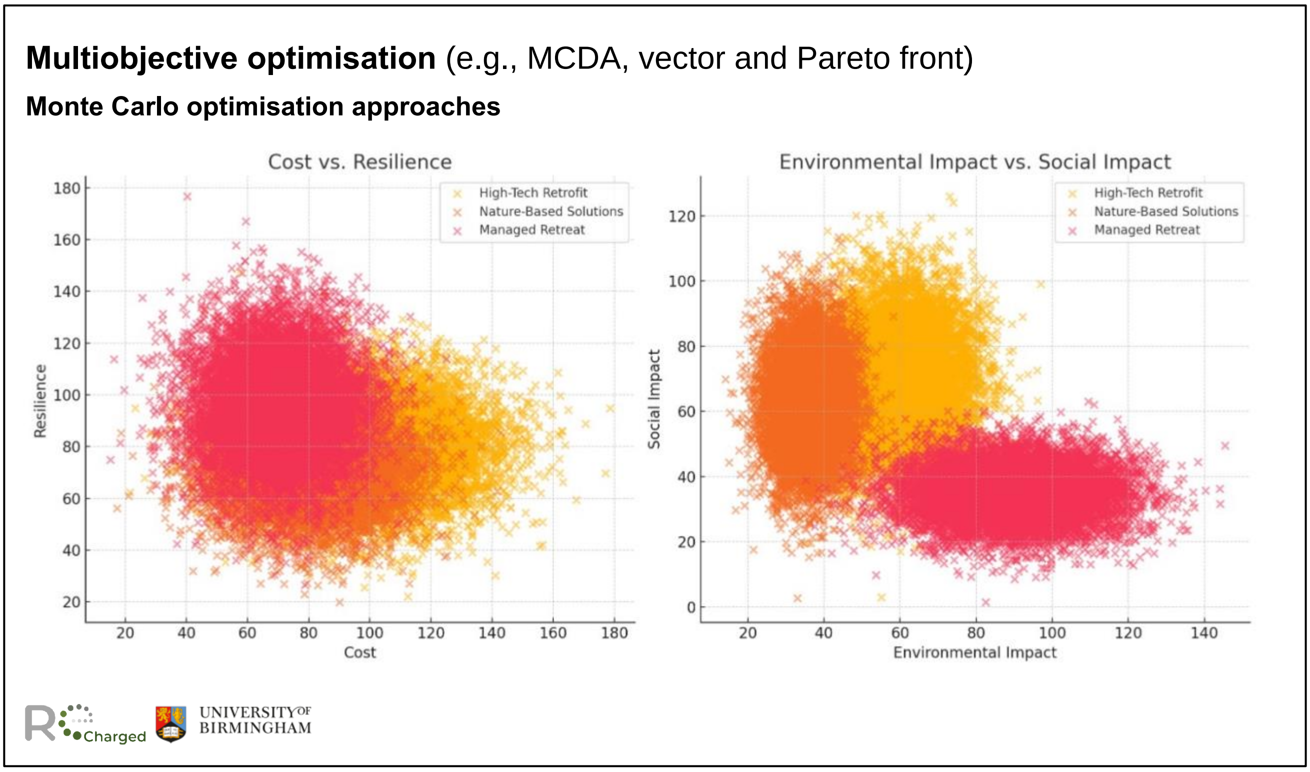
Using Monte Carlo simulation, we randomly generate a large number (e.g., 10,000) of possible scenarios. Each scenario represents that provide the most balanced trade-offs under the uncertainties modeled. For example: a possible future outcome, with different combinations of the values drawn from the distributions defined above.

Step 3: Evaluate Solutions

For each randomly generated scenario, we evaluate multiple possible adaptation strategies, such as:

Solution A: High-tech retrofit.

Solution B: Nature-based solutions.
Solution C: Managed retreat.
Each strategy will produce a set of outcomes for the objectives (cost, resilience, environmental impact, and social impact) based on the scenario conditions.
Step 4: Identify Pareto Optimal Solutions
After running the simulation, we have a large dataset of possible outcomes for each solution.
We then compare these outcomes to determine which solutions are dominated by others (i.e., which are worse across all or most objectives).
Pareto Front Identification: The solutions that are not dominated by any other (i.e., those that provide the best trade-offs across the objectives) form the Pareto front. These are the Pareto optimal solutions.
Step 5: Interpret the Results
The Pareto front represents the set of adaptation strategies
Some solutions might minimize costs but at the expense of resilience.
Others might maximize resilience but with higher costs or environmental impacts.
The Monte Carlo simulation allows decision-makers to visualize and quantify the trade-offs between different objectives under various possible future scenarios. This approach is particularly valuable when dealing with the inherent uncertainties of climate change.



This is a visualization of the Monte Carlo simulation results for different adaptation strategies (High-Tech Retrofit, Nature-Based Solutions, and Managed Retreat) when making decisions about bridge resilience in a climate change context.
Left Plot: Cost vs. Resilience. X-Axis (Cost): Lower values are better; Y-Axis (Resilience): Higher values are better.
This plot shows the trade-off between cost and resilience for each strategy. Ideally, we want to minimize cost while maximizing resilience. You can see the distribution of possible outcomes for each strategy:
High-Tech Retrofit (Yellow): Generally higher resilience but at a higher cost.
Nature-Based Solutions (Orange): Offers a good balance between cost and resilience.

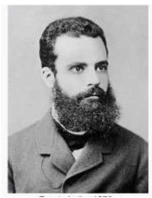
Managed Retreat (Red): Has a widespread, potentially very resilient but often at a high cost.
Right Plot: Environmental Impact vs. Social Impact. X-Axis (Environmental Impact): Lower values are better; Y-Axis (Social Impact): Higher values are better.
This plot shows the trade-off between environmental and social impacts:
High-Tech Retrofit (Yellow): Tends to have higher environmental impact but also potentially higher social benefits.
Nature-Based Solutions (Orange): Lower environmental impact with moderate to high social benefits.
Managed Retreat (Red): Generally, has a lower environmental impact but varying social outcomes, often less favourable.

Multiobjective optimisation (e.g., MCDA, vector and Pareto front)

Pareto Optimal Solution

Formulated by Vilfredo Pareto:

The concept of Pareto front or set of optimal solutions in the space of objective functions in multi-objective optimization problems (MOOPs) stands for a set of solutions that are non-dominated to each other but are superior to the rest of solutions in the search space.



V. Pareto 1848-1932

A point $\bar{x}^* \in F$ is *Pareto optimal* if for every $\bar{x} \in F$ either

$$f_i(\bar{x}) = f_i(\bar{x}^*), \quad i = 1,2,\ldots,k$$

or, there is at least one $i \in \{1,2,\ldots,k\}$ such that

$$f_i(\bar{x}) > f_i(\bar{x}^*)$$

In words, this definition says that $\bar{x}^*$ is *Pareto optimal* if there exists no feasible vector of decision variables $\bar{x}^* \in F$ which would decrease some criterion without causing a simultaneous increase in at least one other criterion

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Multiobjective optimisation (e.g., MCDA, vector and Pareto front)

Pareto Optimal Solution

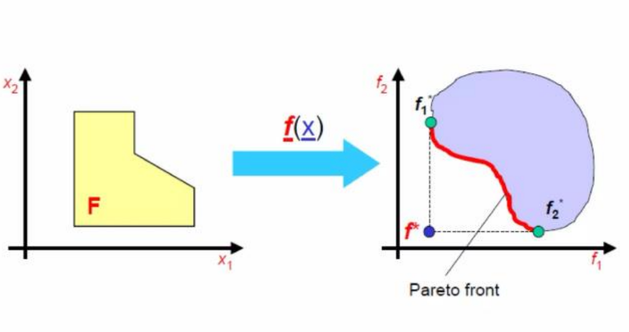
A solution $x \in F$ is said to dominate $y \in F$ if
- ➔ x is better or equal to y in all attributes
- ➔ x is strictly better than y in at least one attribute

Formally, x dominate y ($x \succ y$)

$$f_i(\bar{x}) \le f_i(\bar{y}), \quad i = 1,2,\dots,k$$

$$\exists\, j \in \{1,2,\dots,k\} : f_j(\bar{x}) < f_j(\bar{y})$$

The *Pareto set* consists of solutions that are not dominated by any other solutions



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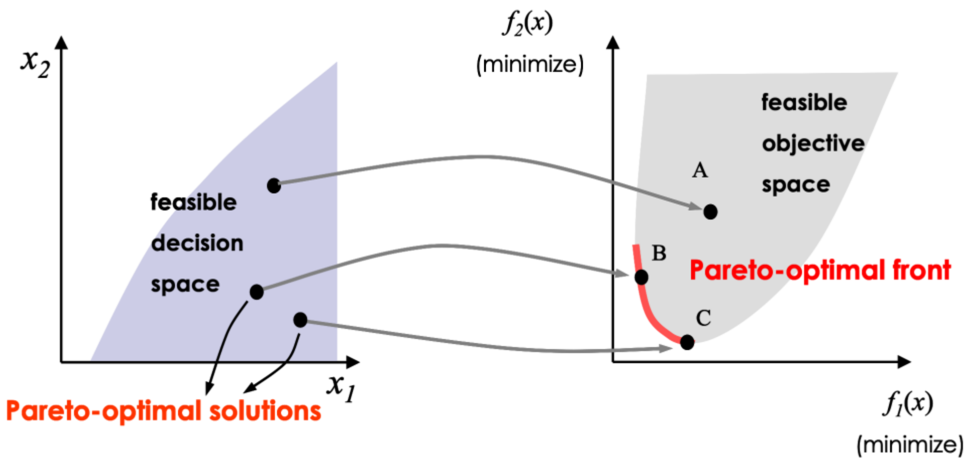
Multiobjective optimisation (e.g., MCDA, vector and Pareto front)

Pareto Optimal Solution



Goals:
Find set of solutions as close as possible to Pareto-optimal front
To find a set of solutions as diverse as possible

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Multiobjective optimisation (e.g., MCDA, vector and Pareto front)

Pareto Optimal Solution - Example

A coastal city has several key bridges that are vulnerable to climate change impacts, such as rising sea levels, increased storm frequency, and heavier rainfall. The city is planning to adapt its infrastructure to improve resilience while managing costs. The decision-making process involves multiple objectives, including:

1. **Cost Minimisation**: Minimising the costs of upgrades, maintenance, and any new infrastructure.
2. **Resilience Maximisation**: Enhancing the ability of the bridges to withstand climate-related stressors.
3. **Environmental Impact Minimisation**: Reducing the environmental footprint of the adaptation measures.
4. **Social Impact Optimisation**: Ensuring the adaptation measures have positive or at least neutral impacts on the local community, including maintaining accessibility and minimizing disruptions.

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Multiobjective optimisation (e.g., MCDA, vector and Pareto front)

Pareto Optimal Solution - Example

Possible Solutions

Solution A: High-Tech Retrofit
- **Cost**: High (Advanced materials and technology are expensive)
- **Resilience**: Very High (Can withstand extreme climate conditions)
- **Environmental Impact**: Moderate (Requires energy-intensive materials, but has a long lifespan)
- **Social Impact**: Moderate (May require temporary closures but offers long-term stability)

Solution B: Natural-Based Solutions (Green Infrastructure)
- **Cost**: Moderate (Leveraging natural materials and processes)
- **Resilience**: Moderate (Good protection against sea-level rise and storm surges, but less effective against heavy loads)
- **Environmental Impact**: Low (Enhances local ecosystems and biodiversity)
- **Social Impact**: High (Improves aesthetics, enhances public spaces, and provides recreational opportunities)

Solution C: Managed Retreat
- **Cost**: Low to Moderate (Depends on the extent of relocation)
- **Resilience**: High (Avoids future risks by relocating infrastructure away from vulnerable areas)
- **Environmental Impact**: High (Potential land disruption and loss of current infrastructure)
- **Social Impact**: Low to Negative (Relocation might disrupt communities and reduce accessibility)

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Multiobjective optimisation (e.g., MCDA, vector and Pareto front)

Pareto Optimal Solution - Example

Pareto Optimal Solution

In resilience-based decision-making for climate change adaptation, a **Pareto optimal solution** would be one where no other solution is better in all objectives. In this context:

• **Solution A** may be preferred if the city prioritizes long-term resilience over costs, and is willing to accept moderate environmental impacts and social disruptions.

• **Solution B** could be the Pareto optimal solution for a balance between moderate costs, good resilience, low environmental impact, and high social benefits.

• **Solution C** might be optimal if the city has limited resources and aims to reduce future risks significantly, even at the cost of current social and environmental impacts.

In this case, **Solution B** might be considered Pareto optimal if:

• **No other solution provides higher resilience without increasing costs, environmental impact, or reducing social benefits.**

• **No other solution has a lower environmental impact without sacrificing too much on resilience or increasing costs.**

This would make Solution B a balanced, Pareto optimal choice, as it optimizes across multiple objectives without any one solution dominating it completely.

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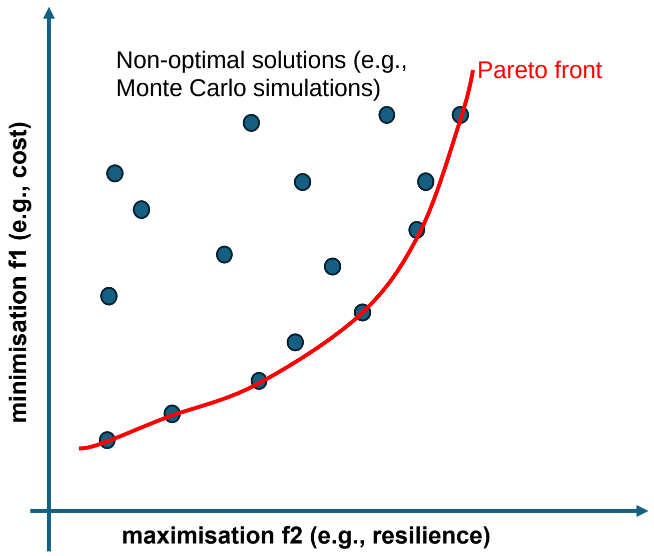
Multiobjective optimisation (e.g., MCDA, vector and Pareto front)

Pareto Optimal Solution - Example



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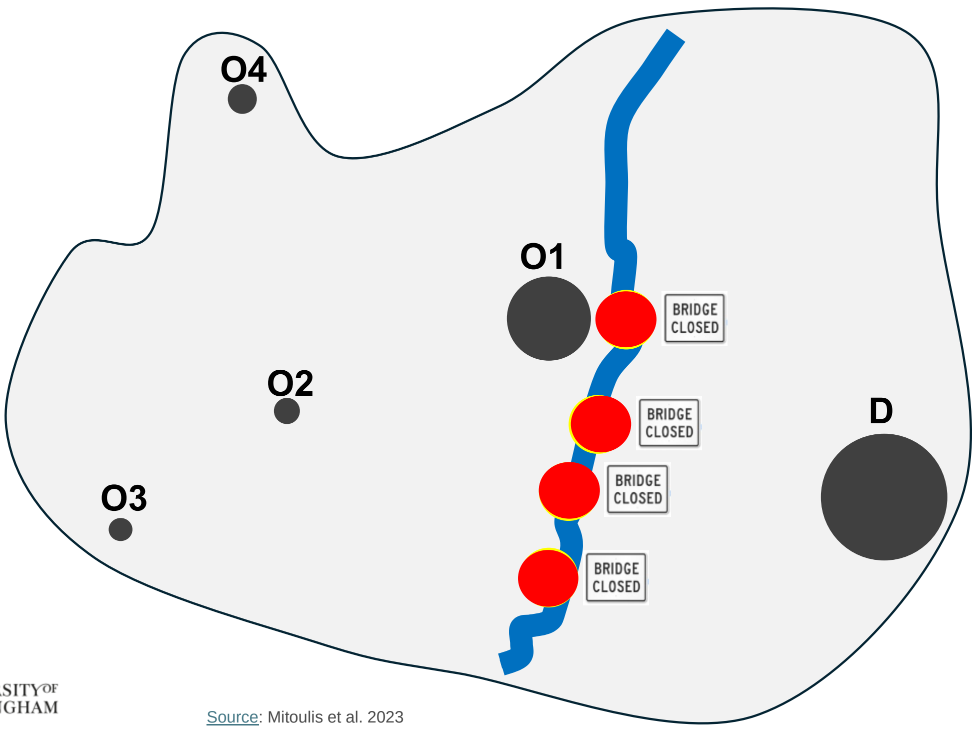
Activity 2. Social impacts and participatory decision making

ACTIVITY 2: Social impacts and participatory decision making

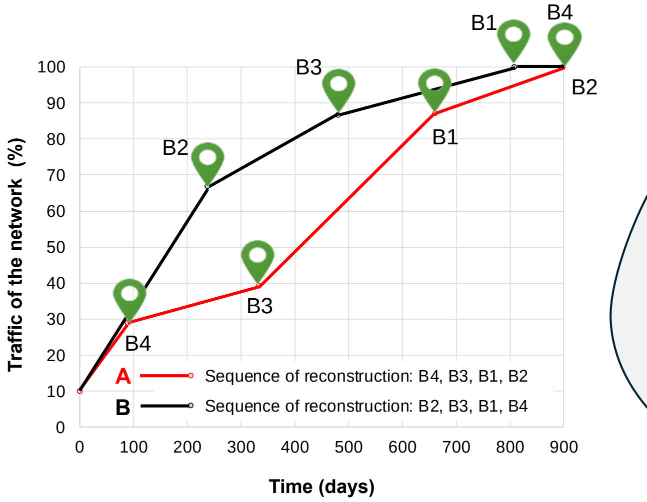
- Example of a critical asset closure and impact assessment
- Consequence analysis

Example of a critical asset closure and impact assessment

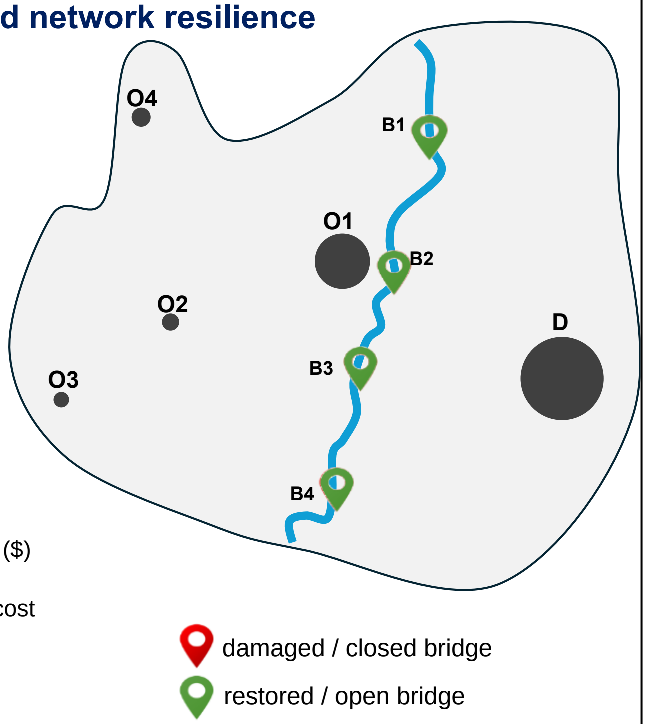


Source: Mitoulis et al. 2023

Prioritisation of restoration based on road network resilience



- 15-20% better traffic performance for the same investment ($) if restoration strategy **B** is adopted instead of **A**
- for limited investment ($) this framework can save 30% of cost and increase 30-35% the network traffic performance
- prioritisation reduces the cost due to traffic detours by 60%



Source: Mitoulis et al. 2023

The proposed prioritisation framework of bridge reconstruction can help increase the traffic capacity of road networks by up to 20%.

The proposed framework can help reduce the cost of reconstruction by up to 30% and hence help optimise decisions under budget restraints.

The same framework can be applied for optimising any infrastructure system reconstruction e.g., health (hospitals- based on people that can be hospitalised), and education (schools- number of students that can access education).

The framework can incorporate different metrics for this optimisation, for example, external donors' requirements, societal needs, resilience and sustainability targets, and visualise optimum solutions on a platform.

Example of a critical asset closure and impact assessment

Geometry, cost and restoration time for the case study bridges

Bridge	Spans	Length (m)	Width (m)	Area (m^2)	Reconstruction cost* (€)	Restoration time** (days)
B1	3	140	26	3640	10,920,000	328
B2	3	120	22	2640	7,920,000	238
B3	2	90	30	2700	8,100,000	243
B4	4	100	10	1000	3,000,000	90

* cost estimated at 3,000 €/m^2 for conventional RC/PC bridges

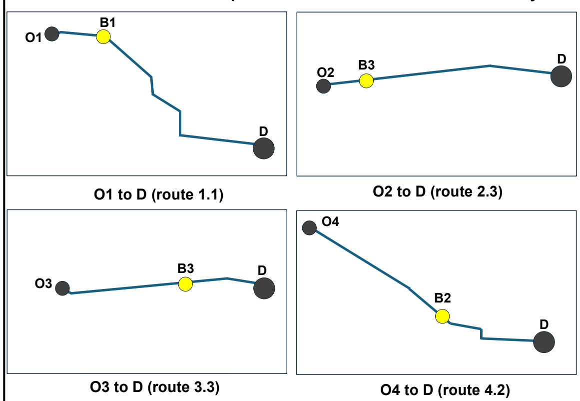
** B4 was the reference bridge, while the restoration time was adjusted based on the area for B1, B2, B3, by a factor of 3.64, 2.64, 2.70, respectively

Source: Mitoulis et al. 2023

Example of a critical asset closure and impact assessment

Representative Origin-Destination (O-D) and alternative routes through the case study bridges

Shortest routes for four representative connections of the case study



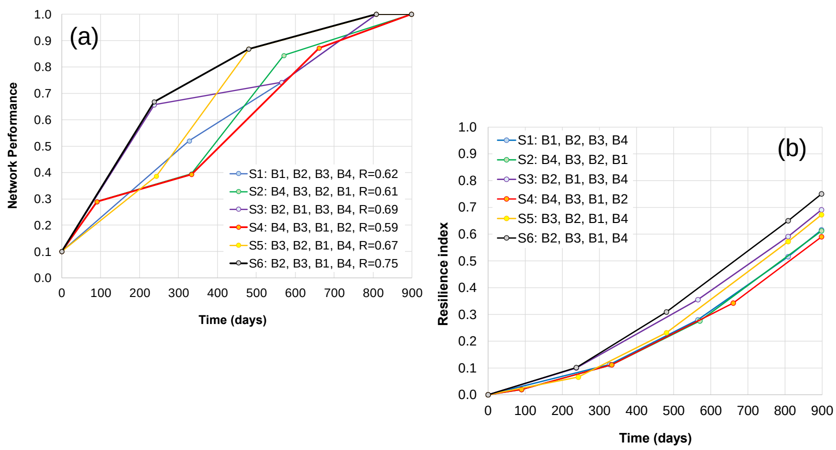
O1 to D (route 1.1) | O2 to D (route 2.3) | O3 to D (route 3.3) | O4 to D (route 4.2)

O-D traffic flow	Alternative routes	Distance (km)	Time (min)	Serving bridge
1. O1-D 16,674 vehicles/day*	1.1	29.87	40	B1
	1.2	32	42	B2
	1.3	50	90	B3
	1.4	50.5	75	B4
2. O2-D 5,201 vehicles/day*	2.1	49.8	60	B1
	2.2	34	43	B2
	2.3	26	31	B3
	2.4	39.2	45	B4
3. O3-D 4,792 vehicles/day*	3.1	82	90	B1
	3.2	64	60	B2
	3.3	56.2	52	B3
	3.4	67.6	64	B4
4. O4-D 5,779 vehicles/day*	4.1	58.4	63	B1
	4.2	56.2	60	B2
	4.3	61.5	62	B3
	4.4	76.3	75	B4

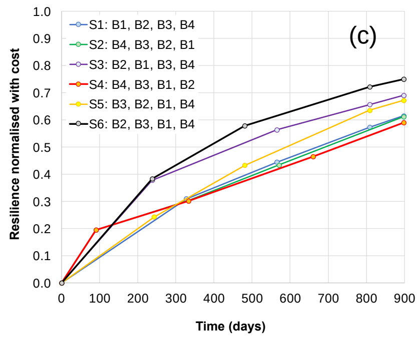
* 10% of the population

Source: Mitoulis et al. 2023

Example of a critical asset closure and impact assessment



Evolution of network performance (a), evolution of resilience index (c) and resilience normalised with cost over time (e) (equal weighting factors (γ_1=γ_2=γ_3= 1.0) and traffic proportional to the population



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Source: Mitoulis et al. 2023

Consequence analysis

Example on bridge closure

Disrupted Transportation:

- Traffic congestion: Closure of a major bridge can divert traffic onto alternative routes, leading to congestion and increased travel times.
- Limited accessibility: Communities or areas that heavily rely on the closed bridge may experience reduced access to essential services, businesses, and resources.
- Detours: Alternative routes may be less efficient or longer, causing inconvenience and potential delays for commuters and businesses.

Economic Impact:

- Business disruptions: Businesses located near the closed bridge may experience decreased foot traffic and reduced customer visits, potentially leading to financial losses.
- Supply chain disruptions: The movement of goods and supplies can be hindered, affecting manufacturing, distribution, and retail operations.
- Increased transportation costs: longer routes and increased fuel consumption can lead to higher transportation costs for businesses and consumers.

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Consequence analysis
Example on bridge closure

Emergency Response Challenges:
- Delayed emergency services: Closure of a bridge can impede the response time of emergency services (firefighters, police, ambulances) to incidents on the other side of the bridge.
- Evacuation difficulties: In case of emergencies requiring evacuation, the closure can complicate evacuation routes and slow down the process

Social and Community Effects: (Chang, 2016)
- Isolation: Communities located on opposite sides of the bridge may feel isolated from one another, impacting social interactions, events, and relationships.
- Reduced quality of life: Increased traffic, noise, and pollution from diverted traffic can negatively affect the quality of life for residents living near alternative routes.

Tourism and Travel Industry:
- Tourism decline: Popular tourist destinations connected by the closed bridge may experience a decrease in visitors due to reduced accessibility.
- Travel disruptions: Travel plans that involve crossing the closed bridge may need to be altered, affecting tourism and travel-related businesses.

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Consequence analysis
Example on bridge closure

Infrastructure Strain:
- Increased wear on alternative routes: Diverted traffic can lead to accelerated deterioration of roads and infrastructure not designed to handle high volumes of traffic.
- Maintenance challenges: If the bridge closure is due to maintenance or repairs, postponing these activities could lead to further deterioration and potentially more costly repairs in the future.

Environmental Impact: (Chang, 2016)
- Air quality: Diverted traffic can lead to increased air pollution and emissions, contributing to environmental and health concerns.

Project Costs and Delays: (Chang, 2016)
- Bridge repair or replacement costs: The closure may be necessary for repair or replacement work, incurring costs and potentially causing delays in completion.

Politics and Public Relations:
- Political fallout: Bridge closures can lead to public dissatisfaction and criticism of local governments and transportation authorities.
- Public relations challenges: Communication and transparency become important to manage public expectations and provide updates on the closure's progress.

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Economic impact of bridge closure

Running cost associated with a detour on a bridge

$$C_{\mathrm{Run}} = \left[c_{\mathrm{Run,car}} \left(1 - \frac{T}{100} \right) + c_{\mathrm{Run,truck}} \frac{T}{100} \right] D \times \mathrm{AADT}$$ *(equation 1)*

$c_{Run,car}$ and $c_{Run,truck}$ are the **average costs for running cars and trucks** per unit length (£/km);
D is the **length of the detour** (km); *AADT* is the **annual average daily traffic to detour**;
and ***T*** the **annual average daily truck traffic ratio** (AADTT, %).
AADT is related to the functionality level of a bridge under given hazard. For example, if the functionality equals 1.0 or 0.0, it means that all traffic is opened or forced to detour, respectively.

The monetary value of time loss for users and goods traveling through the detour and damaged link

$$C_{\mathrm{TL}} = \left[c_{\mathrm{AW}} O_{\mathrm{car}} \left(1 - \frac{T}{100} \right) + \left(c_{\mathrm{ATC}} O_{\mathrm{truck}} + C_{\mathrm{goods}} \right) \frac{T}{100} \right] \times \left[\mathrm{AADT} \times \frac{D}{S} + \mathrm{AADE} \times \left(\frac{l}{S_{\mathrm{D}}} - \frac{l}{S_0} \right) \right]$$ *(equation 2)*

c_{AW} is the **average wage per hour** (£/h); c_{ATC} is the **average total compensation** per hour (£/h);
c_{goods} is the time **value of the goods transported** in a cargo (£/h);
AADE is the **annual average daily traffic remaining** on the damaged link; O_{car} and O_{truck} are the **average vehicle occupancies** for cars and trucks; *l* is the **route segment** (i.e., link) containing the bridge (km);
S_0 and S_D the **average speed on the intact link and damaged link** (km/h); and *S* the **average detour speed** (km/h).

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Dong & Frangopol (2015)

Economic impact of bridge closure

Environmental cost associated with bridge closure

The total economic consequences (C_{TOT}) is the sum of repair loss (C_{REP}), running loss of the detouring vehicles (C_{Run}), time loss due to the unavailability of the highway segment (CTL) and environmental loss (C_{EN}); *see Equation 3.*

Total cost associated with bridge closure

$$C_{\mathrm{TOT}} = C_{\mathrm{REP}} + C_{\mathrm{Run}} + C_{\mathrm{TL}} + C_{\mathrm{EN}}$$ *(equation 3)*

Dong & Frangopol (2015)

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Economic impact of bridge closure – Queensferry Crossing (QFC)

Falling ice causes first Queensferry Crossing closure https://www.bbc.co.uk/

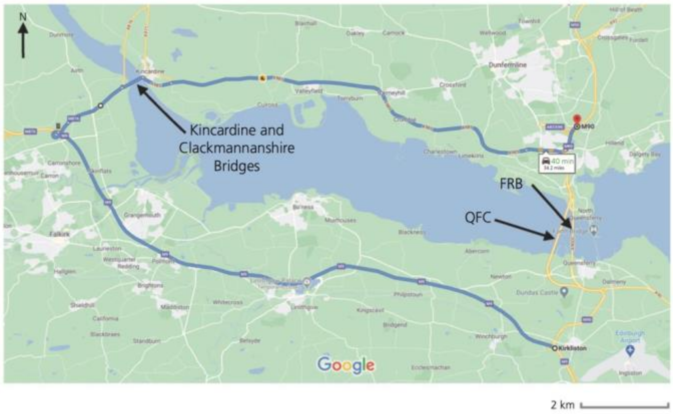
11 February 2020 Share

The Queensferry Crossing has been closed for the first time since it opened in 2017 after ice and snow fell from cables on to vehicles below.

The bridge connecting Edinburgh and Fife was shut on Monday night and will remain closed on Wednesday, the Scottish government said.

Eight vehicles were damaged before the bridge was closed on safety grounds.

the new bridge was closed for ~41 hours,
indirect losses due to traffic diversion:
> £3.6m/day



Smith A, Argyroudis SA, Winter MG, Mitoulis SA (2021). Economic impact of bridge functionality loss from a resilience perspective: Queensferry Crossing. ICE Bridge Engineering

Economic impact of bridge closure – Queensferry Crossing (QFC)

The estimated monetary losses are compared with those of past Forth Road Bridge (FRB) closures.

Parameters of the variables associated with the consequences of QFC and FRB closures

	Value					Reference				
Parameter	**QFC 2020**	**FRB 2015**	**FRB 2016 (1)**	**FRB 2016 (2)**	**FRB 2017**	**QFC 2020**	**FRB 2015**	**FRB 2016 (1)**	**FRB 2016 (2)**	**FRB 2017**
Restoration time: days	1.71	0.29	0.21	0.1	0.79	BBC News (2020c)	Data provided by Transport Scotland for FRB closure durations			
$c_{Run,car}$: £/km	0.40					Average of data taken from Anon (2016) and converted from 'per mile' to 'per km'				
$c_{Run,truck}$: £/km	1.01					Average of data taken from Anon (2018) and converted from 'per mile' to 'per km'				
D: km	56					BBC News (2020a)				
ADTT: %	11.5					Taken for motorways from DfT (2019a)				
AADT: vehicles/day	64319	39851	72951	76000	80620	Data provided by Transport Scotland for Kincardine and Clackmannanshire diversion				
c_{AW}: £/h	14.54	12.98				WebTAG data values Table A1.3.5 for average car in week (DfT, 2019b)				
c_{ATC}: £/h	19.06	17.02				WebTAG 2020 data values Table A1.3.5 for average OGV in week (DfT, 2019b)				
c_{goods}: £/h	2.97	2.54	2.62	2.62	3.16	Value converted from $/h to £/h based on the average exchange rate at the time of closure. Deco and Frangopol (2015)				
O_{car}	2.243					Wong and Winter (2018)				
O_{truck}	1.000					Decò and Frangopol (2011)				
S: km/h	64	64	47	42	48	Data provided by Transport Scotland for Kincardine and Clackmannanshire diversion converted to km/h				
$C_{run,car}$: CO_2 kg/km	0.22					Dong *et al.* (2014)				
$C_{run,truck}$: CO_2 kg/km	0.56					Dong *et al.* (2014)				
Cost value of environmental metric per unit weight (carbon dioxide), C_{Env}: £/kg	0.2					See Anon (2020)				

Smith et al. (2021) https://doi.org/10.1680/jbren.20.00041

Economic impact of bridge closure – Queensferry Crossing (QFC)

Cost	Total (1.7 days)	Per day
Operational cost associated with the detour, C_{Run}: £	2 944 015	1 721 646
Cost of time loss for users and goods travelling through the detour, C_{TL}: £	3 021 481	1 766 948
Environmental cost of carbon dioxide emissions, C_{EN}: £	318 161	186 059
Total economic consequences, C_{TOT}: £	6 283 656	3 674 653
Cost as a percentage of the project value		
Project value: £	1 350 000 000	
Losses to project cost ratio: %	0.47	
Design life: years	120	
Value per day: £	30 822	

The table shows the direct consequential costs estimate for the *41h* bridge **closure of QFC** as well as the corresponding daily cost and comparison ratio to the original project value.

Smith et al. (2021) https://doi.org/10.1680/jbren.20.00041

Economic impact of bridge closure – Forth Road Bridge (FRB)

Closure	9 January 2015		29 January 2016		1 February 2016		11 January 2017	
Duration	7 h–0.29 days		5 h–0.21 days		2.5 h–0.10 days		19 h–0.79 days	
Cost	Total: £	Per day: £	Total: £	Per day: £	Total: £	Per day: £	Total: £	Per day: £
Operational cost associated with the detour, C_{Run}	308 951	1 065 348	409 546	1 950 220	203 173	2 031 729	1 702 637	2 155 237
Cost of time loss for users and goods travelling through the detour, C_{TL}	283 394	977 220	518 331	2 468 242	286 810	2 868 103	2 087 641	2 642 583
Environmental cost of carbon dioxide emissions, C_{EN}	33 386	115 126	44 257	210 748	21 956	219 556	183 993	232 903
Total economic consequences, C_{TOT}	625 731	2 157 694	972 134	4 629 210	511 939	5 119 389	3 974 271	5 030 723
Total economic consequences from all closures (1.4 days): £	6 084 075							
Average total economic consequences from all closures per day: £	4 234 254							
Project value: £	19 500 000							
Losses to project cost ratio: %	3.21		4.99		2.63		20.38	

The table shows the direct consequential economic impacts of the **FRB closures** between 2015 and 2017, with a total cost of £6.08M and an average cost per day of £4.23M.

The construction of the QFC resulted to increased resilience of the network.

Smith et al. (2021) https://doi.org/10.1680/jbren.20.00041

Activity 3. Case study on a critical infrastructure

ACTIVITY 3: Case study on a critical infrastructure

- Resilience and sustainability may be correlated or independent
- Case study on optimising resilience and sustainability metrics

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Resilience and sustainability may be correlated or independent

Challenge
Optimisation of climate resilience and sustainability in adaptation

Gap
Resilience and sustainability consolidation is not adopted by current research and practice in infrastructure adaptation.

Solution
Integrated framework for optimising **resilience** and **sustainability** using low-carbon infrastructure restoration strategies

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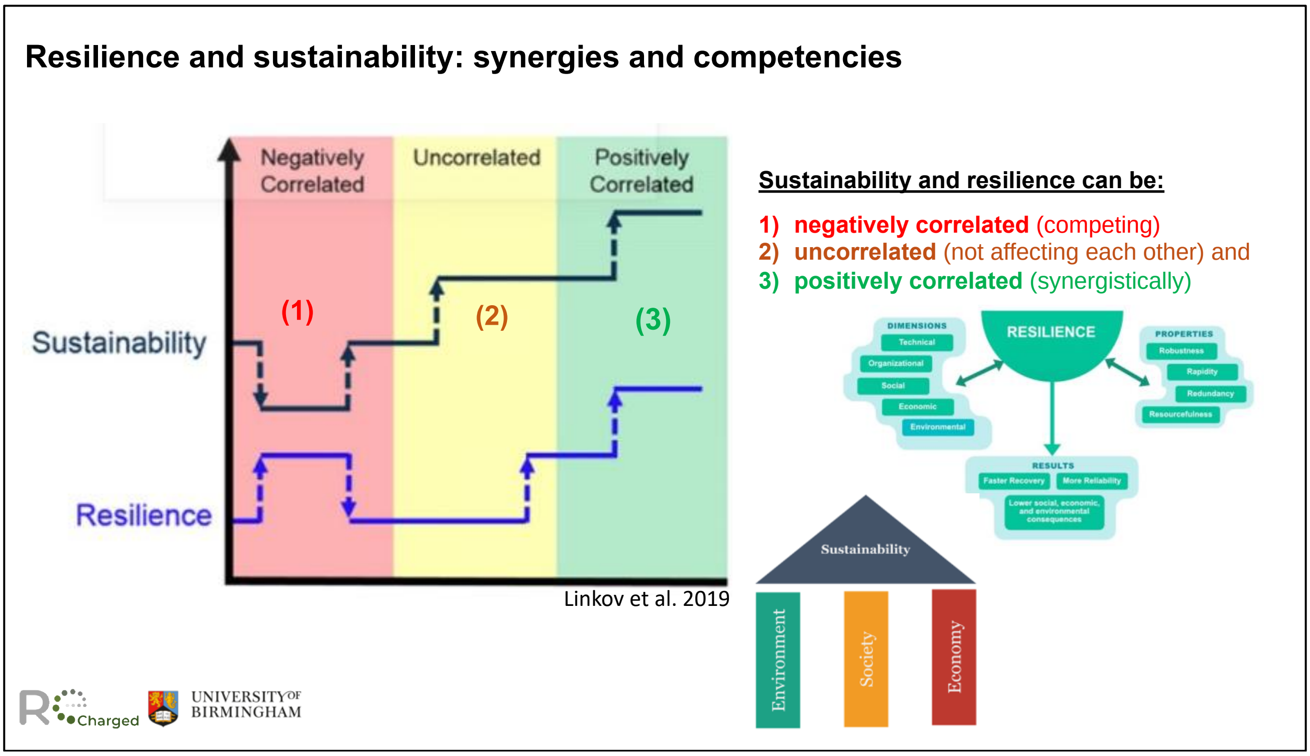
Challenge- Though grey solutions have been streamlined since the concrete era, today we urgently need greener solutions that lead to less tCO2e and more so in the structural sector to be on track with net-zero and sustainable requirements

Gap - Nevertheless, resilience and sustainability consolidation is neither adopted by current research and practice. The integration of these two principles has been introduced by previous frameworks. However, we still lack in practical metrics and representative case studies that facilitate both decision-making for efficient climate adaptation and lower tCO2e in transport infrastructure sector, whilst accounting for limited finances and gradual deterioration of assets.
Novelty - To fill this gap, a novel integrated framework is needed, for optimising resilience and sustainability metrics to minimise the cost using traditional and low-carbon grey restoration strategies in the event of floods affecting critical transport assets.



Today's discussion focuses on the relationship between sustainability and resilience, which are two critical goals in managing complex systems such as urban planning, infrastructure development, and environmental conservation. While both concepts aim to enhance the longevity and functionality of systems, they don't always align perfectly. This slide highlights three possible relationships between sustainability and resilience: negatively correlated, uncorrelated, and positively correlated.

1. Negatively Correlated (Competing Relationship):

In some cases, sustainability and resilience can work against each other, creating a trade-off situation. This is represented in the red-shaded area of the diagram. Here, increasing resilience (e.g., by building highly robust infrastructure) can reduce sustainability, perhaps by increasing resource consumption, carbon emissions, or environmental degradation. For instance, constructing flood barriers might enhance resilience against flooding, but the environmental impact of the materials used might compromise sustainability goals. In such scenarios, achieving one objective (either resilience or sustainability) could be at the cost of the other, leading to a competing relationship.

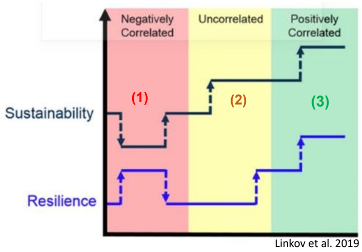
2. Uncorrelated (No Significant Interaction):

The yellow-shaded area represents situations where sustainability and resilience do not significantly influence one another. In this uncorrelated relationship, actions taken to improve resilience do not directly impact sustainability, and vice versa. For example, improving social resilience through community engagement might not directly affect environmental sustainability. The system in this case operates independently in terms of resilience and sustainability, without major synergies or conflicts between the two goals.

3. Positively Correlated (Synergistic Relationship):

In an ideal scenario, sustainability and resilience support each other, leading to a positive, synergistic relationship, as shown in the green-shaded area. In this situation, efforts to enhance resilience simultaneously improve sustainability, and vice versa. For example, promoting renewable energy systems can both improve resilience (by diversifying energy sources and reducing dependency on fossil fuels) and enhance sustainability (by reducing carbon emissions). This positive correlation is the desired outcome, where strategies that target one goal also contribute to the other.

Resilience and sustainability: synergies and competencies



Examples:

2) **Using different materials to restore a bridge** impacts on tCO2e (i.e. environment / **Sustainability**) but as long as restoration times remain the same the **Resilience** of the road/railway network remains the same.

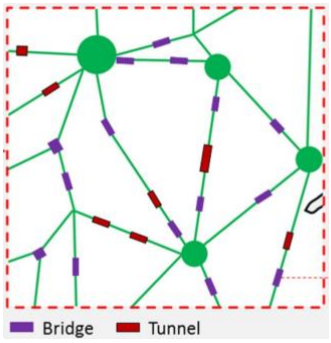
less tCO2e more Sustainable

rip-rap and gabions

more tCO2e less Sustainable

reinforced concrete

Resilience of network unaffected



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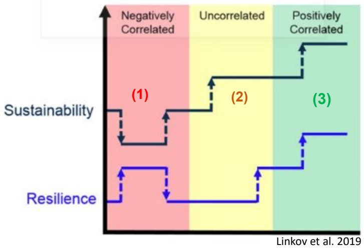
Resilience and sustainability: synergies and competencies



Examples:

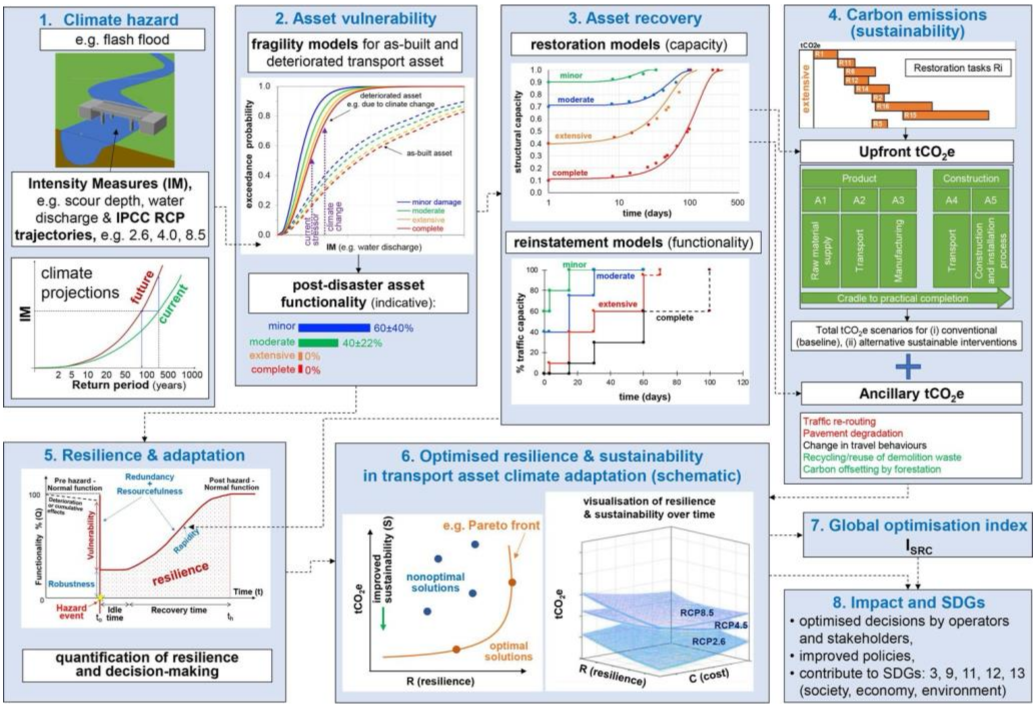
3) Using Nature-based Solutions for strengthening a road or rail embankment both reduces tCO2e (improve **sustainability**) in the long term and improves the **resilience** of the road/rail

…green is more acceptable by the society (improves sustainability)

but…
- Costs
- Duration, Resilience (e.g. after natural disasters)
- Constructability, Viability

Justice et al. of Presto Geosystems (2020)

Framework for optimising resilience and sustainability



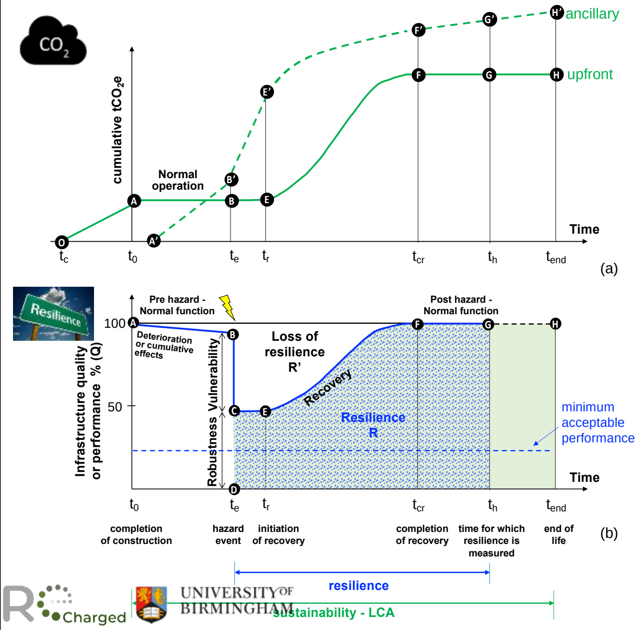
Source: Mitoulis, et al. 2023

The framework shown in the Figure describes the approach for quantifying ex-ante adaptation and post-ante recovery from the lenses of sustainability and resilience in a changing climate. The main steps of the framework are:

Step 1. In this step, the hazard intensity measures (IM) are defined based on predicted, measured or estimated hazard data, using e.g., high-resolution flood maps to deduce probabilistic relationships of

established IM, e.g. peak water depth, streamflow velocity, and discharge, for each one of the affected assets. The fluctuations in the IM, e.g., peak river flow, can be linked to the increased annual probability of exceedance, i.e., the frequency of the hazard, as a result of climate change projections. Based on these projections, information on the potential range of climate exacerbations of floods in the specific location, for different return periods, and emission scenarios can be defined.
Step 2. The vulnerability for the as built and the deteriorated asset is estimated using fragility functions from the literature. The curves correlate the probability of exceeding given damage states (e.g. minor, moderate, extensive, complete) with the hazard IM (see lecture 2).
Step 3. The asset recovery is evaluated based on restoration (structural capacity) and reinstatement (traffic capacity) models, which correlate the asset functionality to the recovery time after the event, considering its typology, damage state, available resources, and post-hazard idle times. In this paper, the modelling of the recovery strategies followed available models from the literature
Step 4. Carbon emissions are quantified considering grey and green restoration measures. Two main emission groups are considered: (i) the upfront emissions, correspond with the carbon associated with the construction works included in the restoration tasks; (ii) the ancillary emissions. refer to the environmental impacts related to traffic re-routing, pavement degradation, change in travel behaviours or recycling and reuse of materials from construction and demolition works within a restoration task. In
Step 5 the resilience to hazard occurrences is quantified with focus on the structural capability of the asset to withstand a hazard occurrence based on a probabilistic assessment, by calculating the weighted capacity using the occurrence probabilities of different damage states for a given IM.
Step 6 An integrated metric is proposed based on resilience, sustainability, and cost to create analytics for decision making.

Case study on optimising resilience and sustainability metrics



Baseline scenario, without regular maintenance.

(a) Evolution of cumulative tCO_2e. Solid line shows upfront and dashed line shows ancillary tCO2e

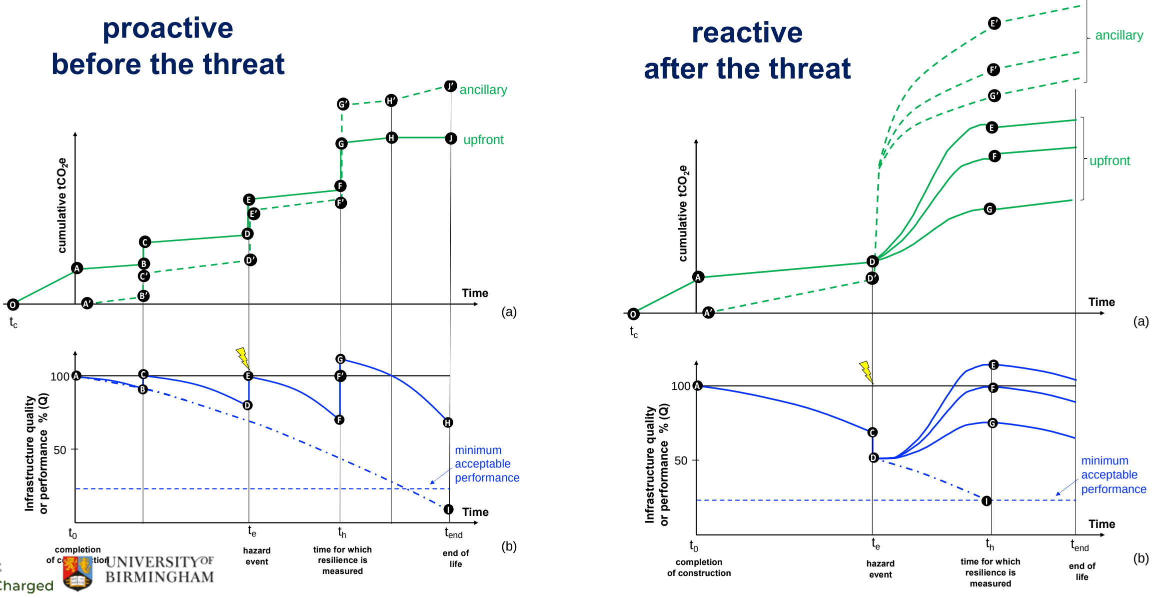
(b) resilience, expressed as quality or performance of infrastructure responding to a hazard occurrence

O: commencement of construction,
A: completion of construction, bridge open to traffic
AB: bridge operates with minimal maintenance or inspection
A'B': tCO2e increase because the bridge operates with decreased functionality and as a result vehicle detours are required
BE: bridge is damaged, but no action is taken (idle time)
B'E': tCO2e increased rapidly as bridge is partially/completely closed and as a result traffic is diverted
EF: restoration measures are being implemented
E'F': ancillary tCO2e due to the implementation of restoration measures, including traffic detour
FH: post-disaster normal function, no maintenance
F'H': similar to A'B'

Source: Mitoulis, et al. 2023

Case study on optimising resilience and sustainability metrics

Proactive vs reactive adaptation strategies



Case study on optimising resilience and sustainability metrics

$$T_R = -\frac{T_L}{\ln(1-P_R)}$$

Step 1. In this step, the hazard intensity measures (IM) are defined based on predicted, measured or estimated hazard data.

$$P_f(DS \geq DS_i | IM) = \Phi\left[\frac{1}{\beta_{tot}} \ln\left(\frac{IM}{IM_{m,i}}\right)\right]$$

Step 2. The vulnerability for the as built and the deteriorated asset is estimated using fragility functions.

Step 3. The asset recovery is evaluated based on restoration (structural capacity) and reinstatement (traffic capacity) models as per Mitoulis et al. 2021.

Step 4. The whole life carbon emissions are quantified. The impact assessments were undertaken by employing the Intergovernmental Panel on Climate Change (IPCC, 2021) approach.

$$tCO2e_j = \sum \lambda_f Q_{i,m} F_{i,m}$$

λ_f is a scalar factor to account for the restoration task duration (λ_f=1 for mean durations)
Q is the quantity of the pollutant emitted to the environment
F is the equivalent carbon factor.

Case study on optimising resilience and sustainability metrics

$$C(T=t) = \sum_{i=0}^{n} C(DS_i | T=t) \cdot P(DS=DS_i \mid IM)$$

Step 5 the resilience is quantified with focus on the structural capacity of the asset to withstand a hazard occurrence (probabilistic assessment, by calculating the weighted capacity using the occurrence probabilities of different DS for a given IM)

where $P(DS=DS_i \mid IM) = P(DS \geq DS_i \mid IM) - P(DS \geq DS_{i+1} \mid IM)$

Step 6, 7 and 8. These steps optimise the metrics of resilience (R) and sustainability (S).

Resilience

$$R_j = \frac{1}{(t_h - t_e)} \int_{t_e}^{t_h} C(t)dt$$

Sustainability metric

$$S_j = \frac{tCO2e_j(T=t_h)}{\max(tCO2e)}$$

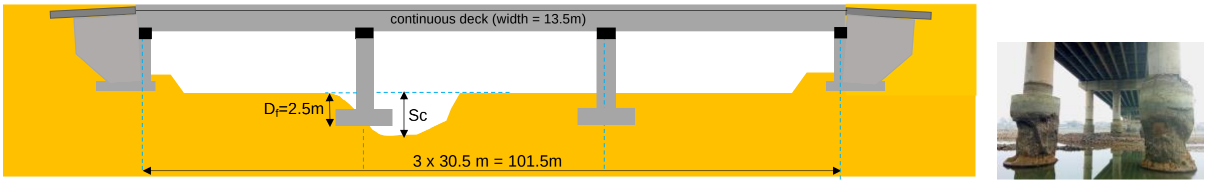
tCO2e

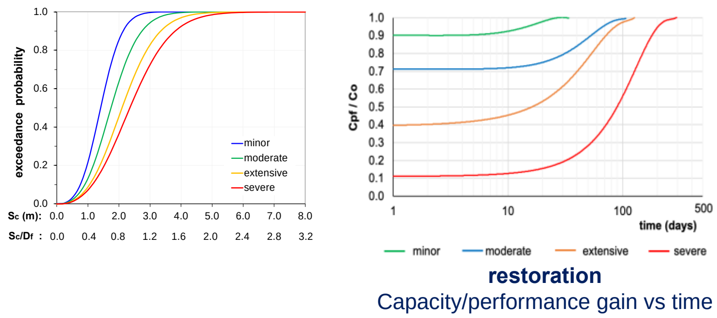
$$tCO2e_j(T=t) = \sum_{i=0}^{n} tCO2e(DS_i | T=t) \cdot P(DS=DS_i \mid IM)$$

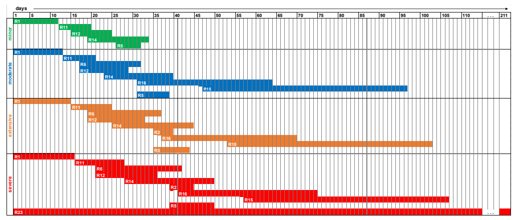
$$C_j = \frac{C_j(T=t_h)}{\max(C)}$$

$$\max(tCO2e) = \max(\{tCO2e_j(T=t_h), : j=1,\ldots, k\})$$

Case study on optimising resilience and sustainability metrics

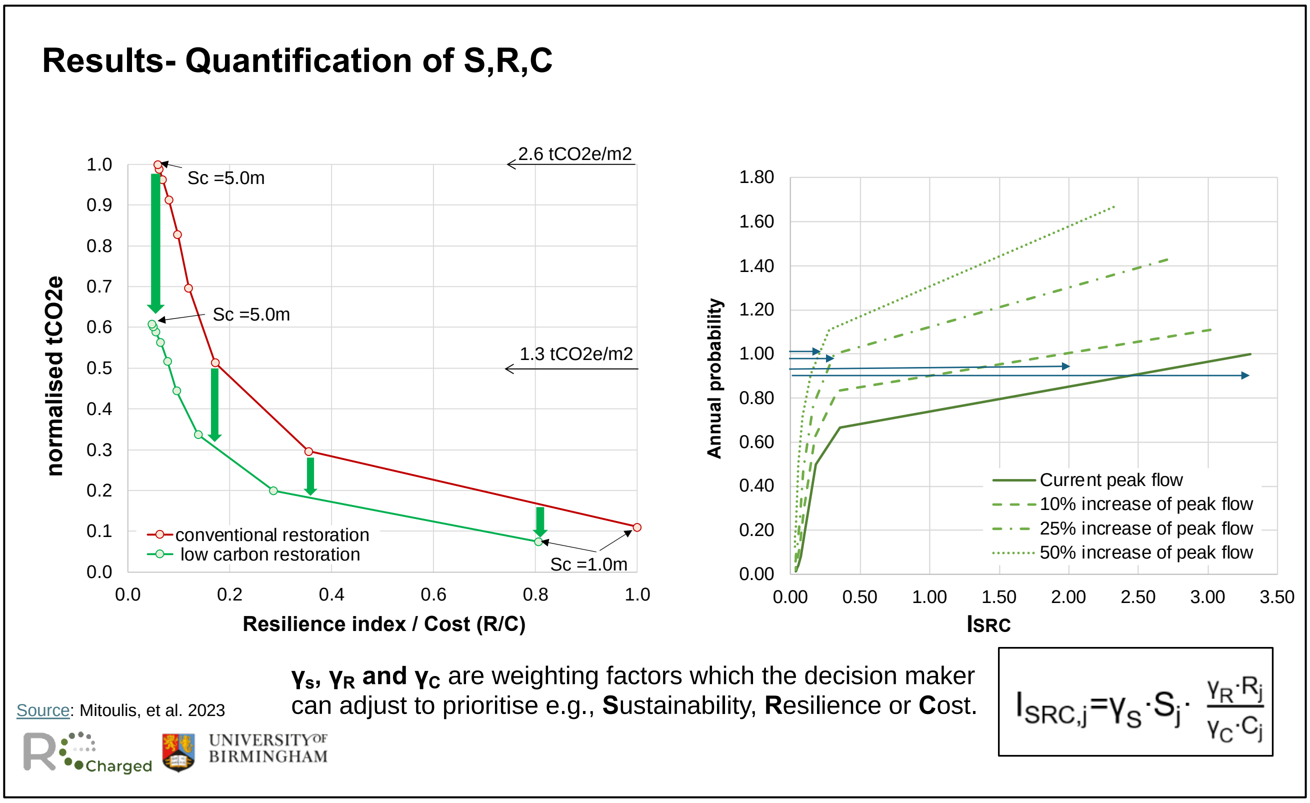


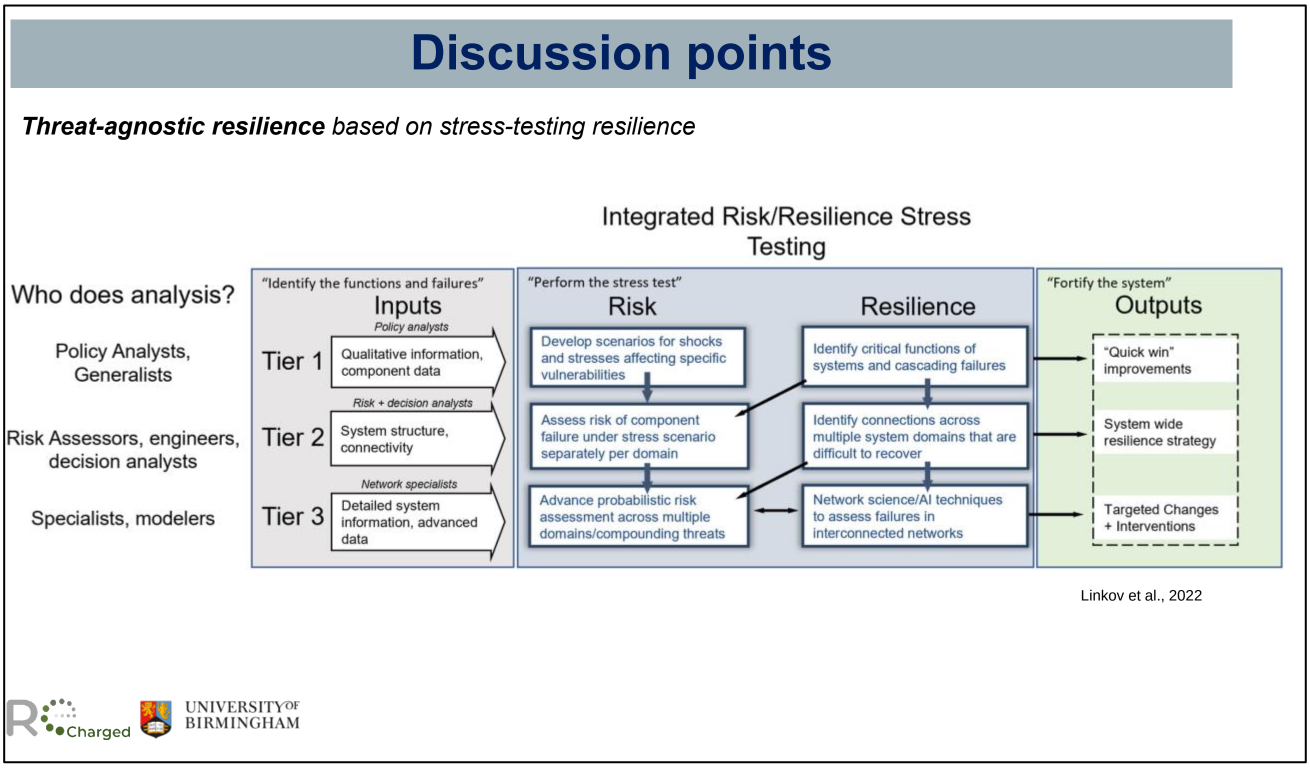




		Conventional materials (mean values of tCO2e)				Low carbon solution (1) (3) (4)	Influence duration
No	Action type	Materials	On-site activities	Trans-portation	Total	%	%
R1	armouring countermeasures and flow-altering/cofferdam	16.9	63.6	0.1	80.6	-14.9	±49.8
R2	temporary support per pier	2.7	4.9	0.1	7.7	-9.6	±30.6
R3	temporary support of one abutment	3.1	6.3	0.2	9.7	-9.9	±35.3
R4	temporary support of one deck span /segment (midspan or support)	1.6	2.4	0.1	4.1	-9.2	±29.8
R5	repair cracks and spalling with epoxy and/or concrete	18.3	1.1	1.2	20.6	-17.6	±3.8
R6	re-alignment and/or levelling of pier	3.4	0.7	0.1	4.2	-13.4	±7.5
R7	re-alignment of bearings	1.1	0.6	0.0	1.7	-4.8	±19.1
R8	jacketing or local strengthening (pier or abutment or foundation)	2.6	0.4	0.0	3.0	-7.3	±6.1
R9	jacketing or local strengthening (deck)	2.7	0.3	0.0	3.0	-0.4	±3.7
R10	re-alignment of deck segment	4.2	4.9	0.1	9.2	-10.3	±20.2
R11	erosion protection measures	645.5	29.0	3.5	678.0	-4.6	±1.7
R12	rip-rap and/or gabions for filling of scour hole and scour protection	21.7	2.5	0.1	24.3	-1.0	±6.1
R13	removal of debris	0.0	0.4	0.0	0.4	-4.8	±44.2
R14	ground improvement per foundation	29.0	5.0	0.3	34.3	-1.3	±7.0
R15	installation of deep foundation system	235.0	113.9	0.4	349.2	-38.3	±10.5
R16	extension of foundation footing	346.5	16.2	0.2	362.9	-57.4	±1.7
R17	reconstruction/replacement of the abutment and wingwalls	902.0	43.2	1.7	946.9	-53.7	±1.8
R18	reconstruction/replacement of the pier	382.6	6.7	0.8	390.2	-54.8	±0.5
R19	temporary support and replacement of the bearings	11.2	0.5	0.2	11.9	-4.5	±1.9

The reference bridge of the case study. (b) Fragility curves of the bridge as a function of the scour depth (Sc) and the normalised Sc / D_f (D_f: foundation depth). (c) Restoration curves of the bridge as a function of time (C_{pf}: post-flood capacity, C_o: original capacity), and (d) Sequence of restoration tasks for the four damage states (minor, moderate, extensive and complete). Description of the activities per task is given in Table A2.





A structured approach to conducting integrated risk and resilience stress testing is presented, focusing on how different tiers of analysts contribute to the process, from gathering inputs to generating actionable outputs.

Overview: Who Does the Analysis?

The framework categorizes the analysts involved into three tiers:

- **Tier 1:** Policy Analysts and Generalists
- **Tier 2:** Risk Assessors, Engineers, and Decision Analysts
- **Tier 3:** Specialists and Modelers

Each tier plays a distinct role in gathering data, performing analysis, and interpreting results, contributing to a comprehensive understanding of both risks and resilience within complex systems.

Process Flow: From Inputs to Outputs

The process is divided into three main stages: **Inputs**, **Risk and Resilience Analysis**, and **Outputs**.

1. Inputs: “Identify the Functions and Failures”

- **Tier 1:** At this stage, policy analysts focus on collecting qualitative information and component-level data. This might include broad, high-level insights on system operations and potential vulnerabilities.
- **Tier 2:** Risk assessors and engineers analyze the system’s structure and connectivity, understanding how different components interact.
- **Tier 3:** Specialists dive into detailed system information and advanced datasets, which include precise metrics and probabilistic data to support deeper analysis.

The goal of this stage is to gather a range of data and insights that can feed into a stress test that examines both risks and resilience.

2. Risk and Resilience Analysis: “Perform the Stress Test”

This stage is the core of the framework, where analysts assess both risks and resilience by simulating stress scenarios.

- **Risk Assessment:**
    - **Tier 1:** Analysts develop scenarios that simulate shocks or stresses impacting specific system vulnerabilities.
    - **Tier 2:** They assess the risk of component failures under these stress scenarios, examining how different parts of the system might fail under pressure.
    - **Tier 3:** Advanced techniques, including probabilistic risk assessments, are used to evaluate cascading failures across multiple domains or interacting systems.
- **Resilience Assessment:**
    - **Tier 1:** Analysts identify critical functions within the system and potential cascading failures that could compromise resilience.
    - **Tier 2:** They also assess connections between different domains of the system, pinpointing areas where recovery might be difficult due to high interdependencies.
    - **Tier 3:** Advanced approaches, such as network science and AI, are used to model resilience across interconnected networks and complex scenarios.

This analysis provides a comprehensive view of the system’s vulnerabilities and its capacity to recover from disruptions.

3. Outputs: “Fortify the System”

The outputs from the stress testing process inform strategic decisions to enhance system resilience. These outputs are categorized into three levels of interventions:

- **“Quick Wins” Improvements:** Immediate, easily implementable actions that can quickly enhance resilience.
- **System-Wide Resilience Strategy:** Broader, long-term strategies that address resilience across the entire system.
- **Targeted Changes and Interventions:** Specific actions focused on high-risk areas or critical system functions identified during the analysis.