Climate-aware Resilience for Sustainable Critical and Interdependent Infrastructure Systems enhanced by emerging Digital Technologies

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

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Lecture 6

Massive Open Online Course

Resilience, Sustainability & Digitalisation in Critical Infrastructure

Optimisation of resilience and sustainability

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Lecture 6 Outcomes

- 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.

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:

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

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

Mathematical formulation

Find the vector

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

Which will satisfy the *m* inequality constraints

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

The *p* equality constraints

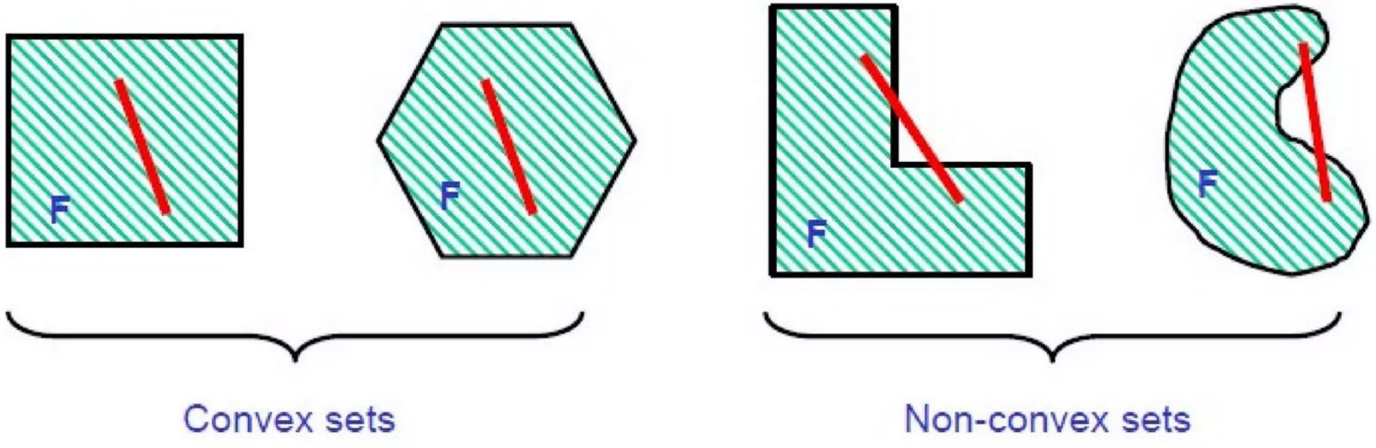
$$h_i(\bar{x}) = 0 \quad i = 1,2,\ldots,p$$

And optimizes the vector function

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

Feasible region

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

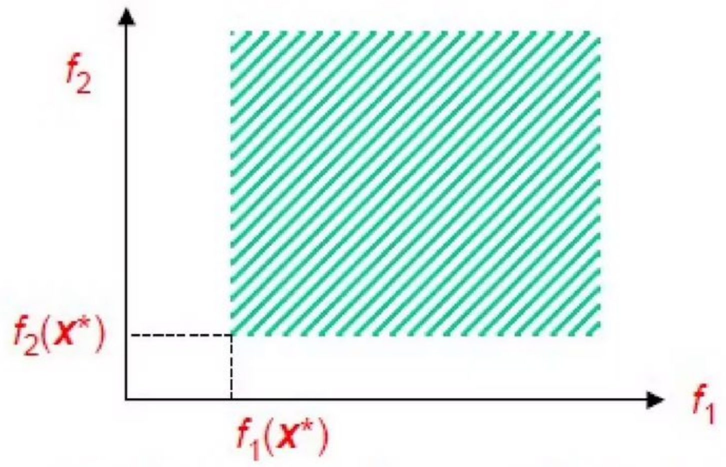


Multiobjective optimisation (e.g., MCDA, vector and Pareto front)

Meaning of optimum

We rarely have an $\mathbf{x}^*$ such that

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



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.

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.

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

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

Monte Carlo optimisation approaches

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

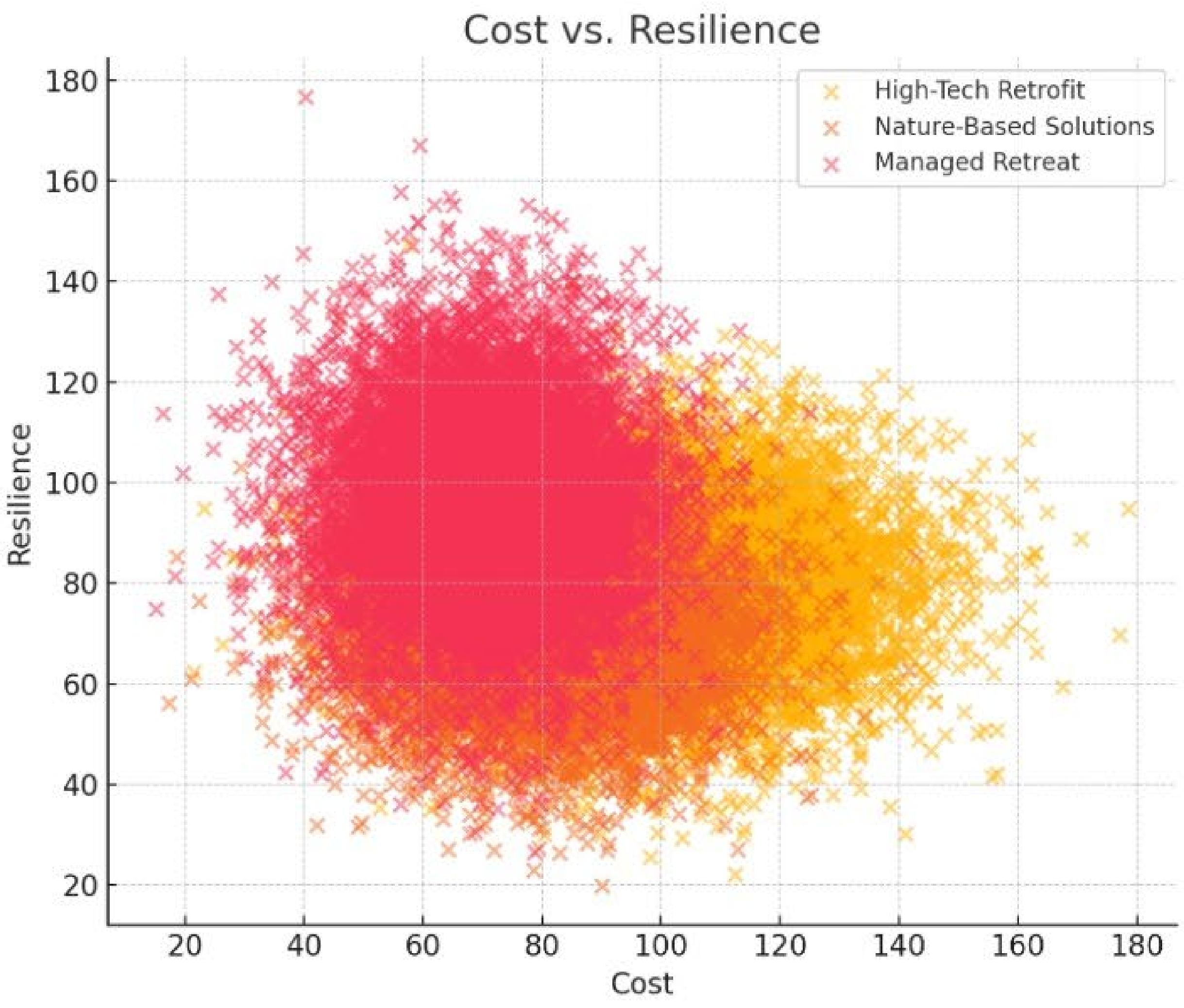
Step 1: Define the Uncertainties

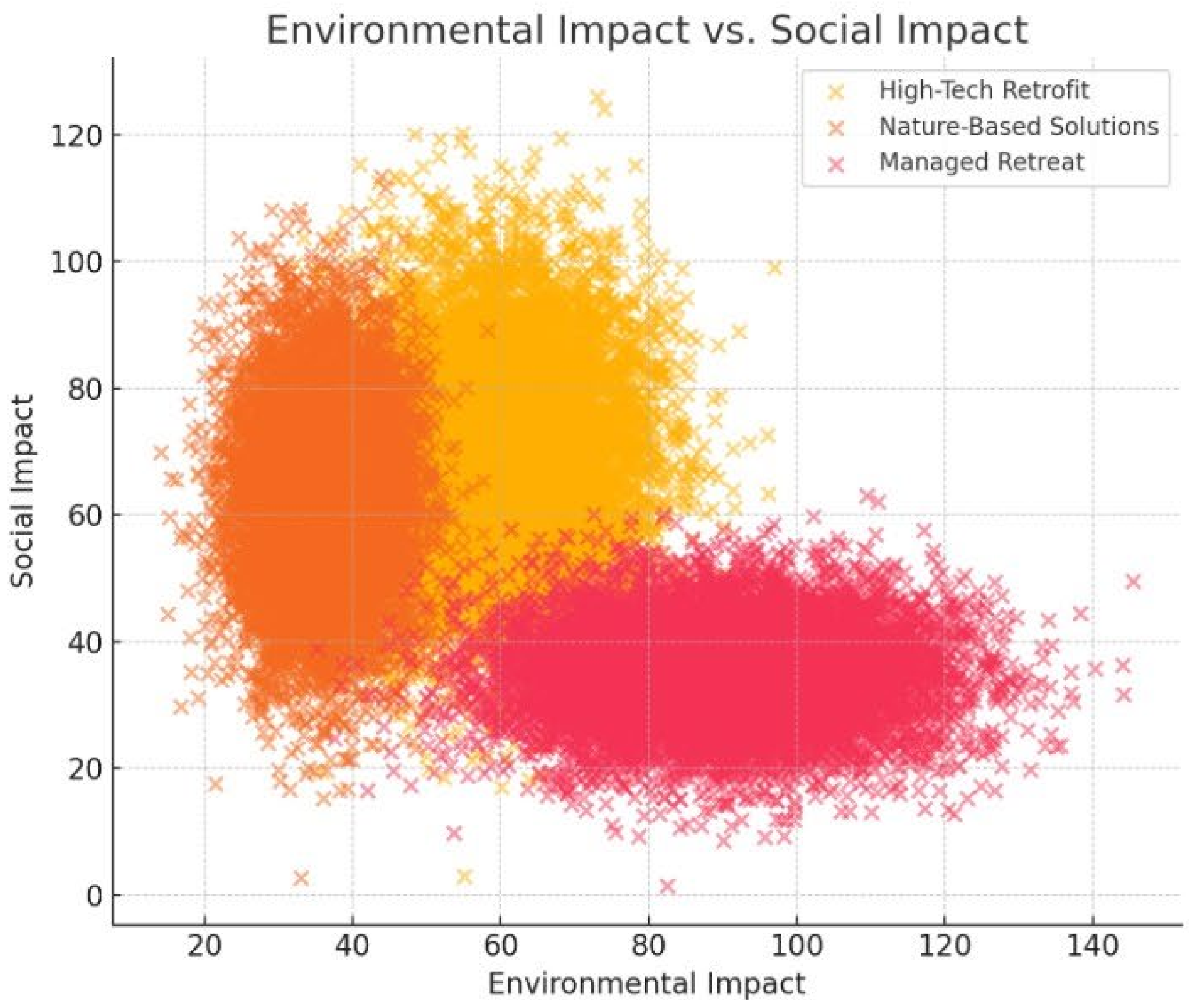
For each objective (cost, resilience, environmental impact, social impact), there are uncertainties related to future climate scenarios, material costs, technological effectiveness, and community responses. We assign probability distributions to these uncertainties:

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.

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

Monte Carlo optimisation approaches



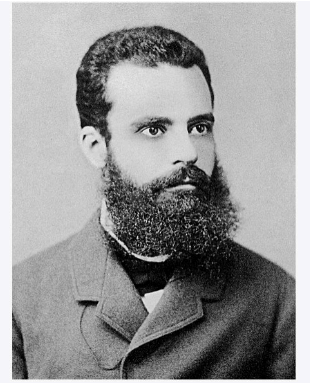


Multiobjective optimisation (e.g., MCDA, vector and Pareto front)

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

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

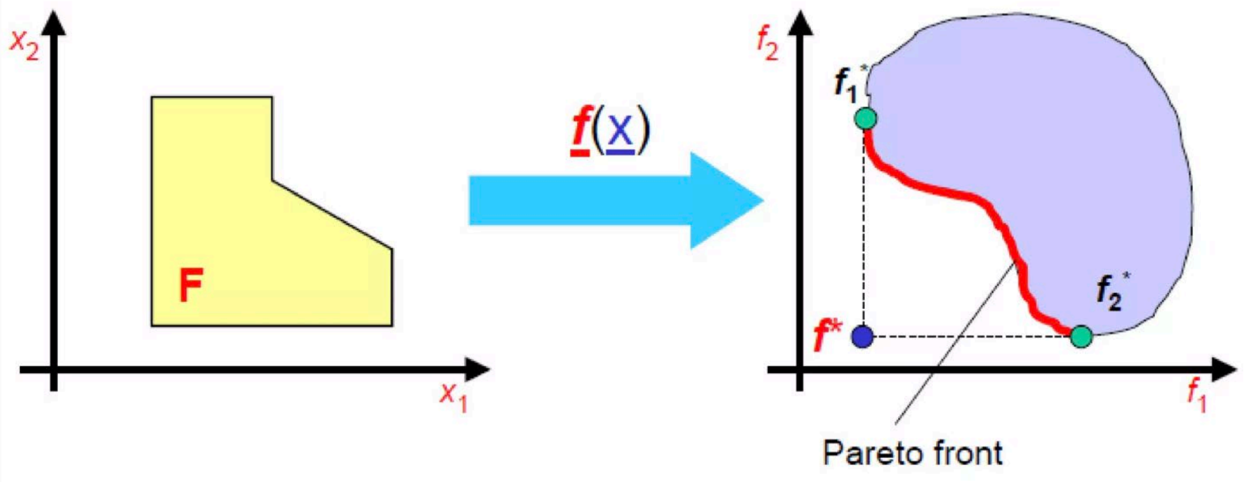
- ➔ x is better or equal to y in all attributes
- ➔ x is strictly better than y in at least one attribute

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

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

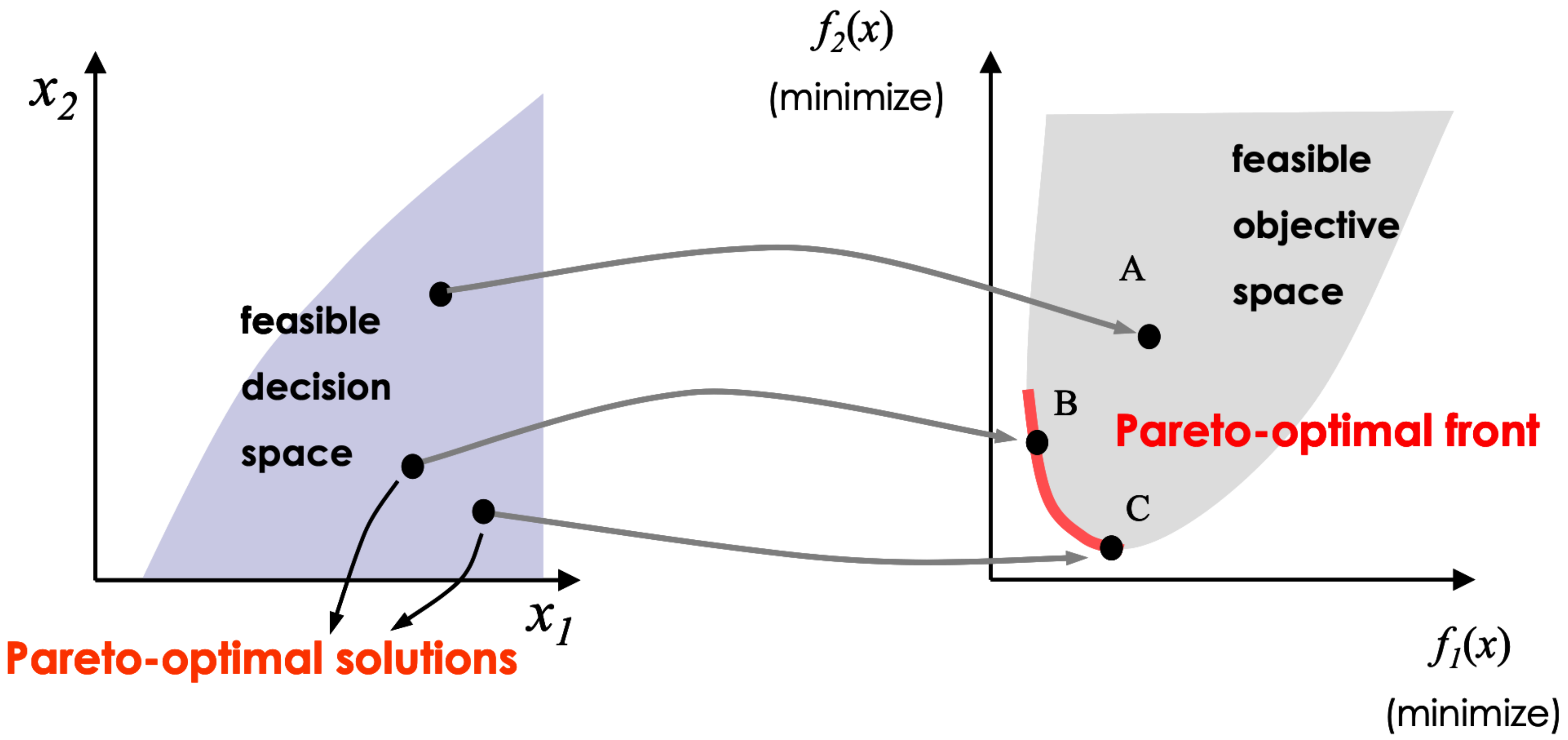
$$\exists\, j \in \{1,2,\ldots,k\} : f_j(\bar{x}) < f_j(\bar{y})$$

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



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

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.

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)

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.

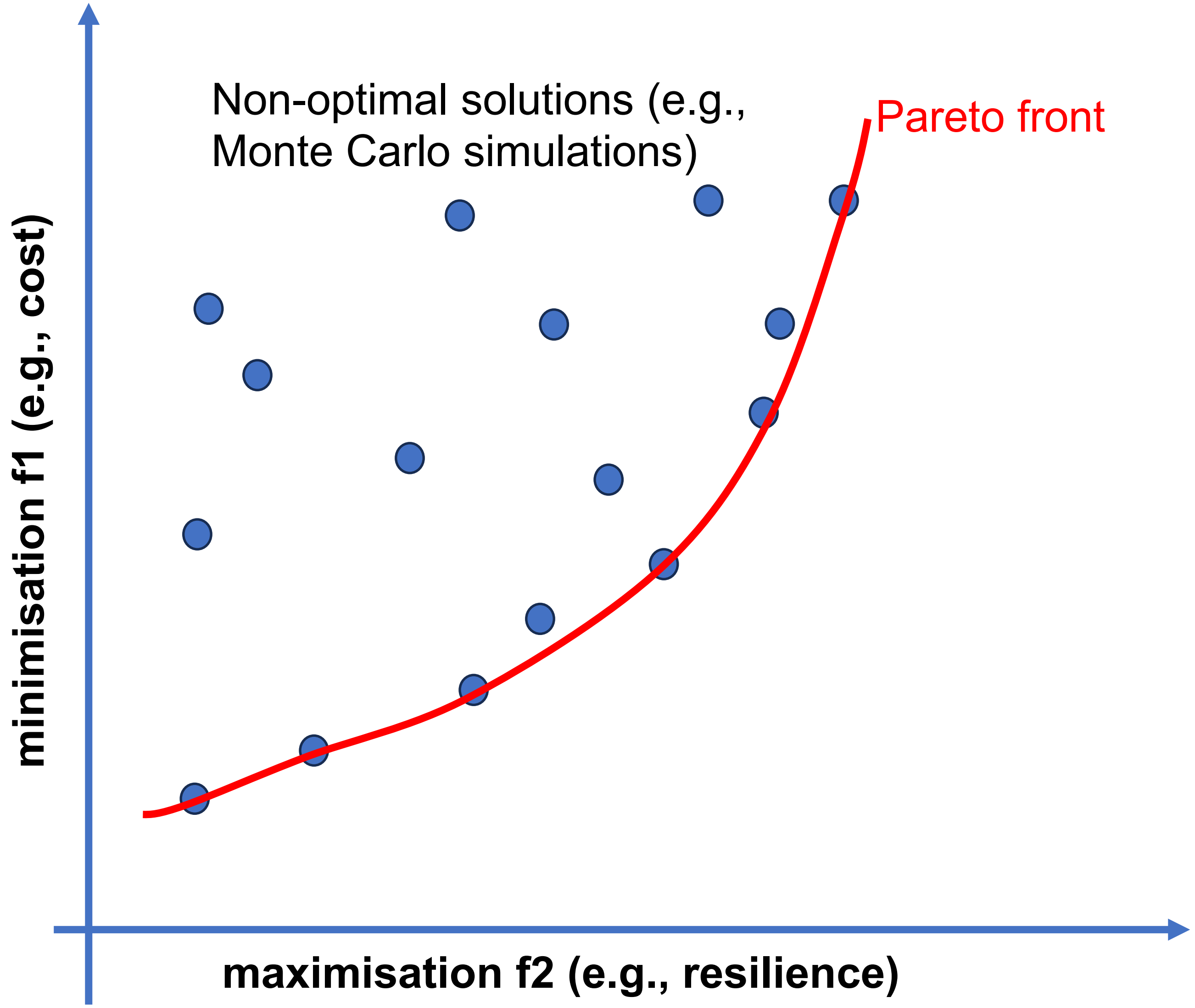
In this case, **Solution B** might be considered Pareto optimal if:

- **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.

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

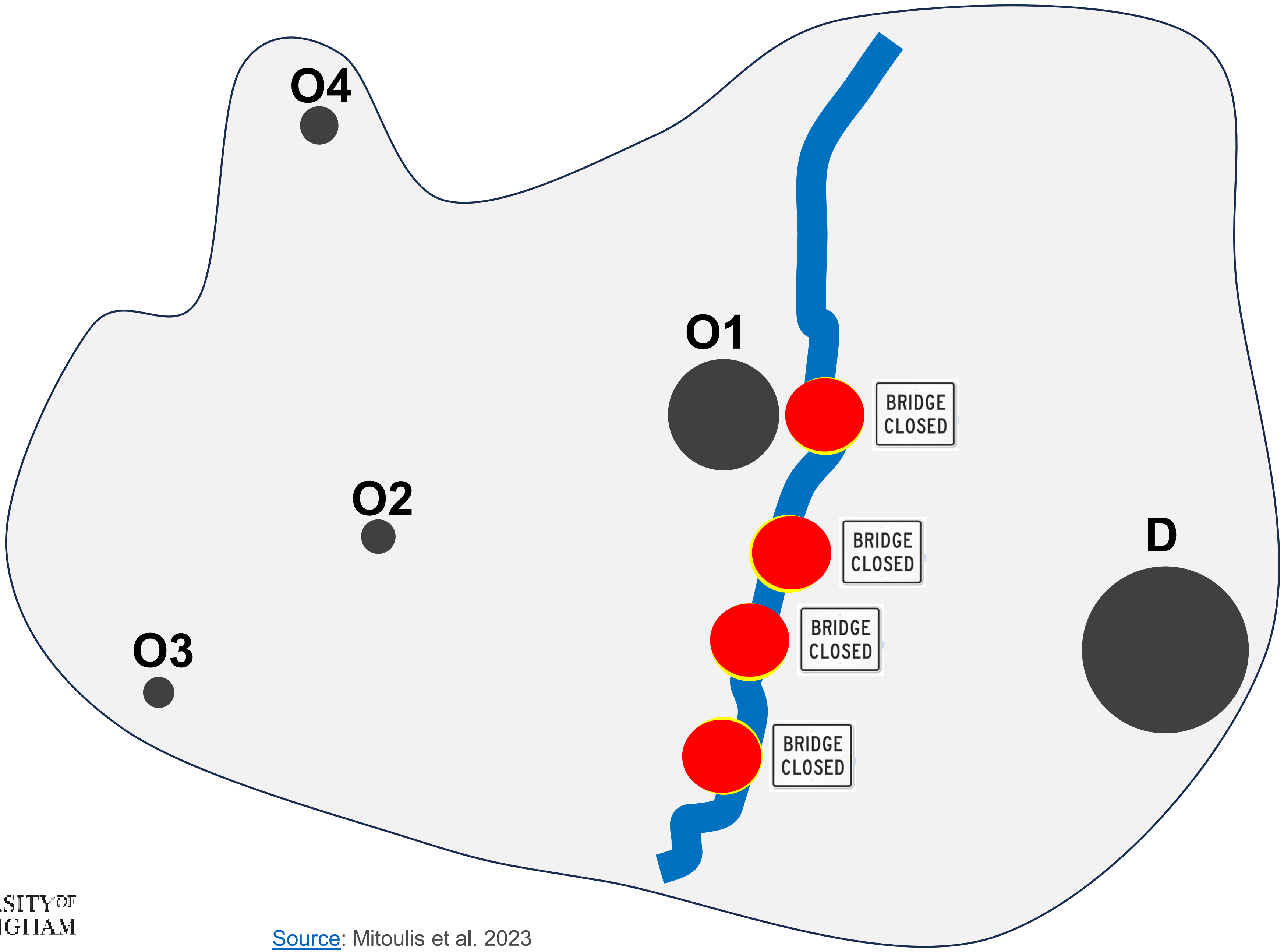
Pareto Optimal Solution - Example



ACTIVITY 2: Social impacts and participatory decision making

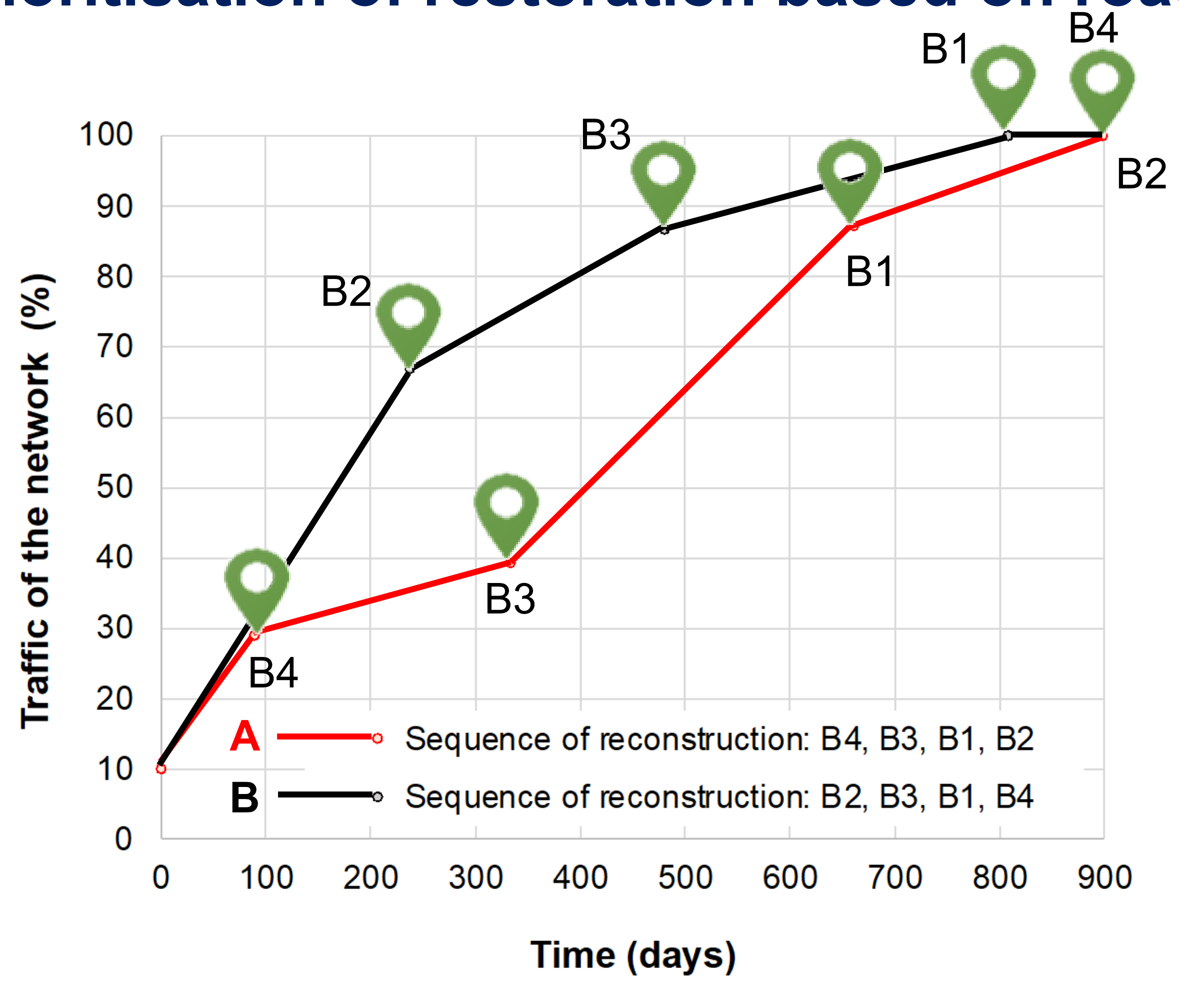
- Example of a critical asset closure and impact assessment
- Consequence analysis

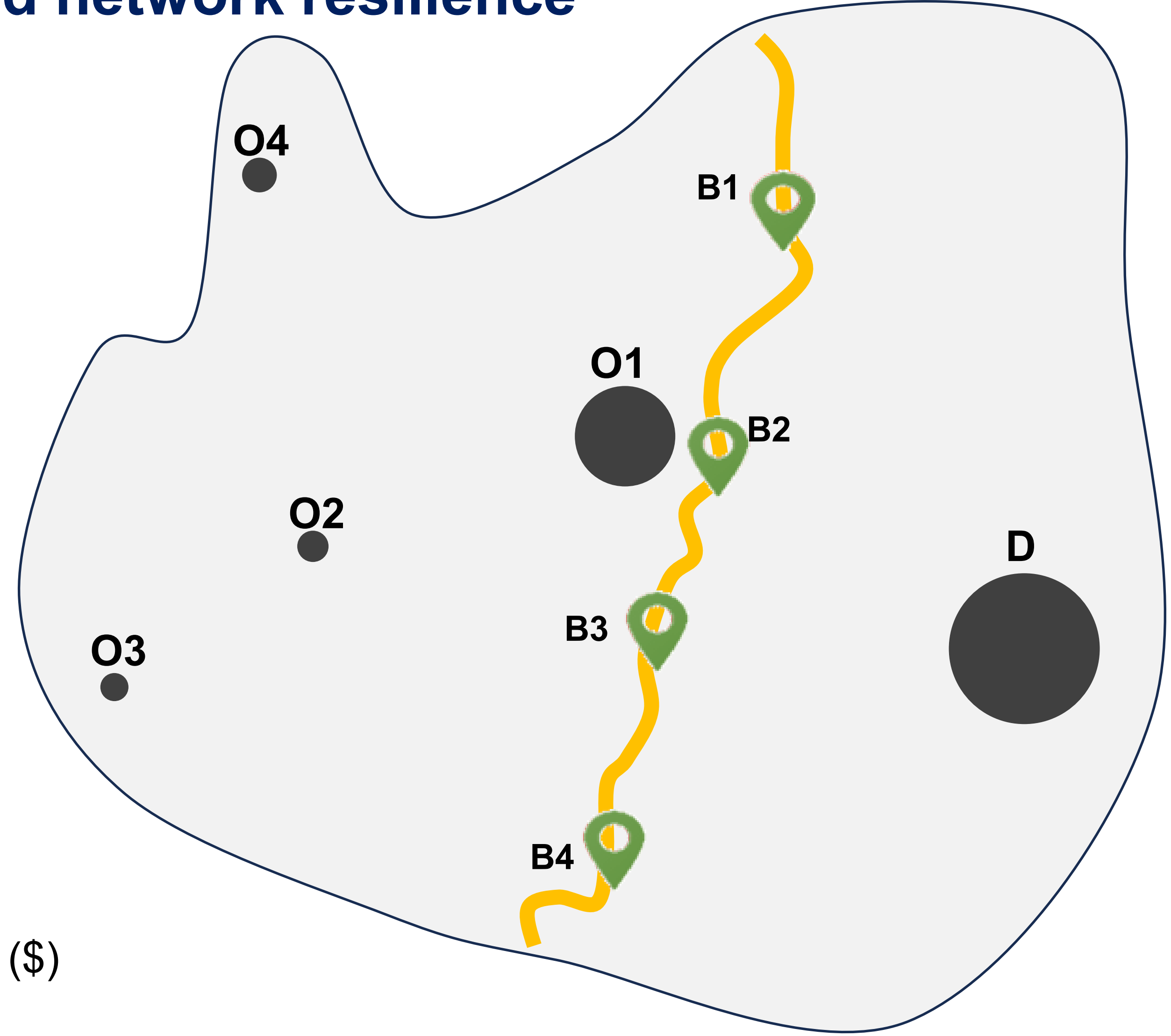
Example of a critical asset closure and impact assessment



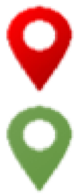
Source: Mitoulis et al. 2023

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

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

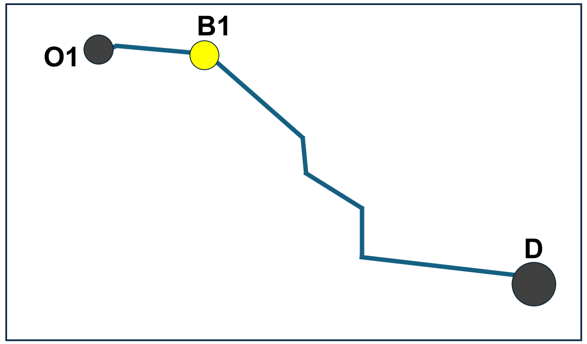
* cost estimated at 3,000 €/m^2 for conventional RC/PC bridges

** 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

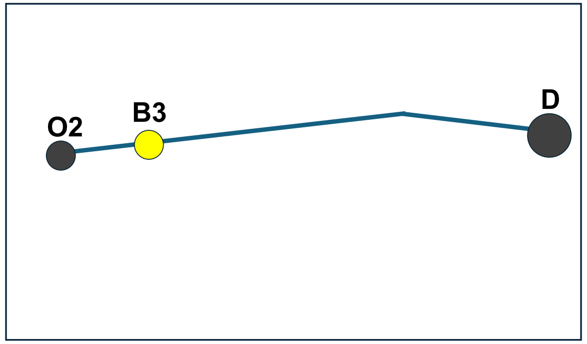
Example of a critical asset closure and impact assessment

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

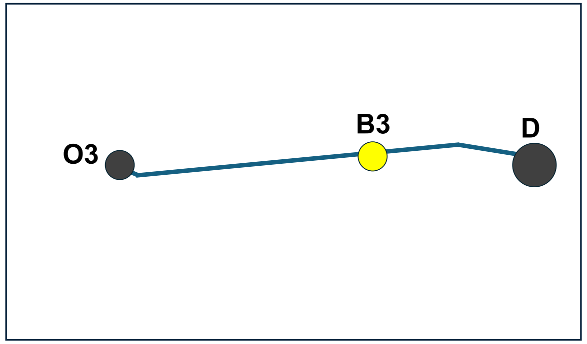
Shortest routes for four representative connections of the case study



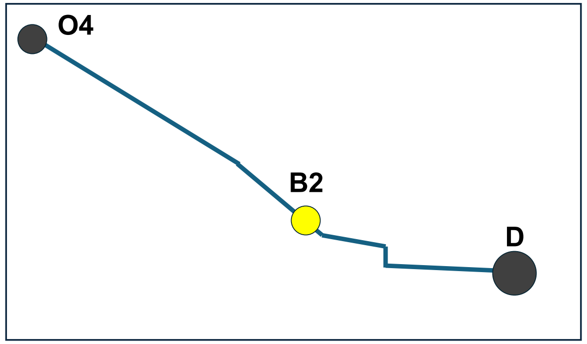
O1 to D (route 1.1)



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

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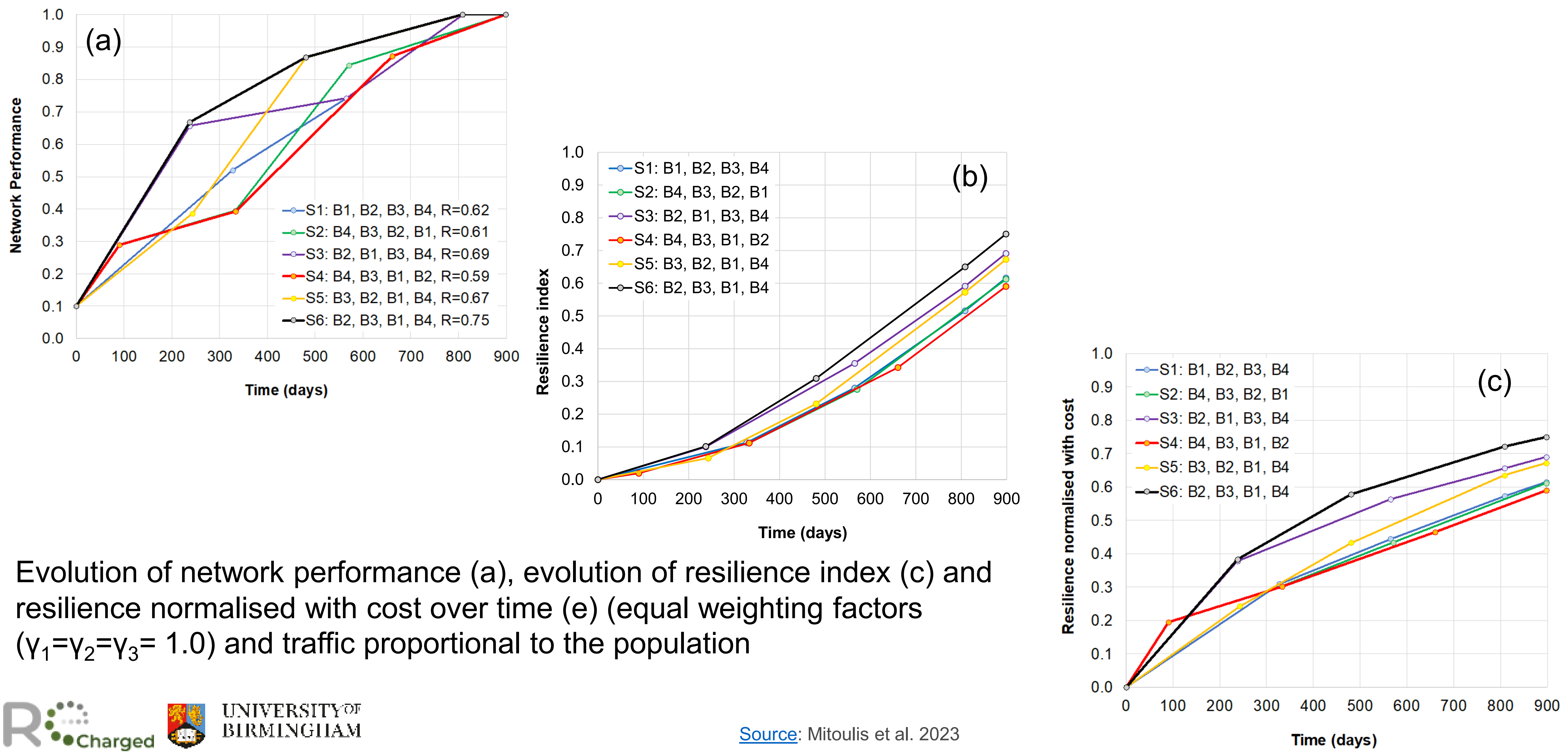
Example of a critical asset closure and impact assessment



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

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.

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.

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.

Economic impact of bridge closure

Running cost associated with a detour on a bridge

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

$c_{Run,car}$ 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

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

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).

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

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

Dong & Frangopol (2015)

Economic impact of bridge closure – Queensferry Crossing (QFC)

Falling ice causes first Queensferry Crossing closure

https://www.bbc.co.uk/

11 February 2020

Share

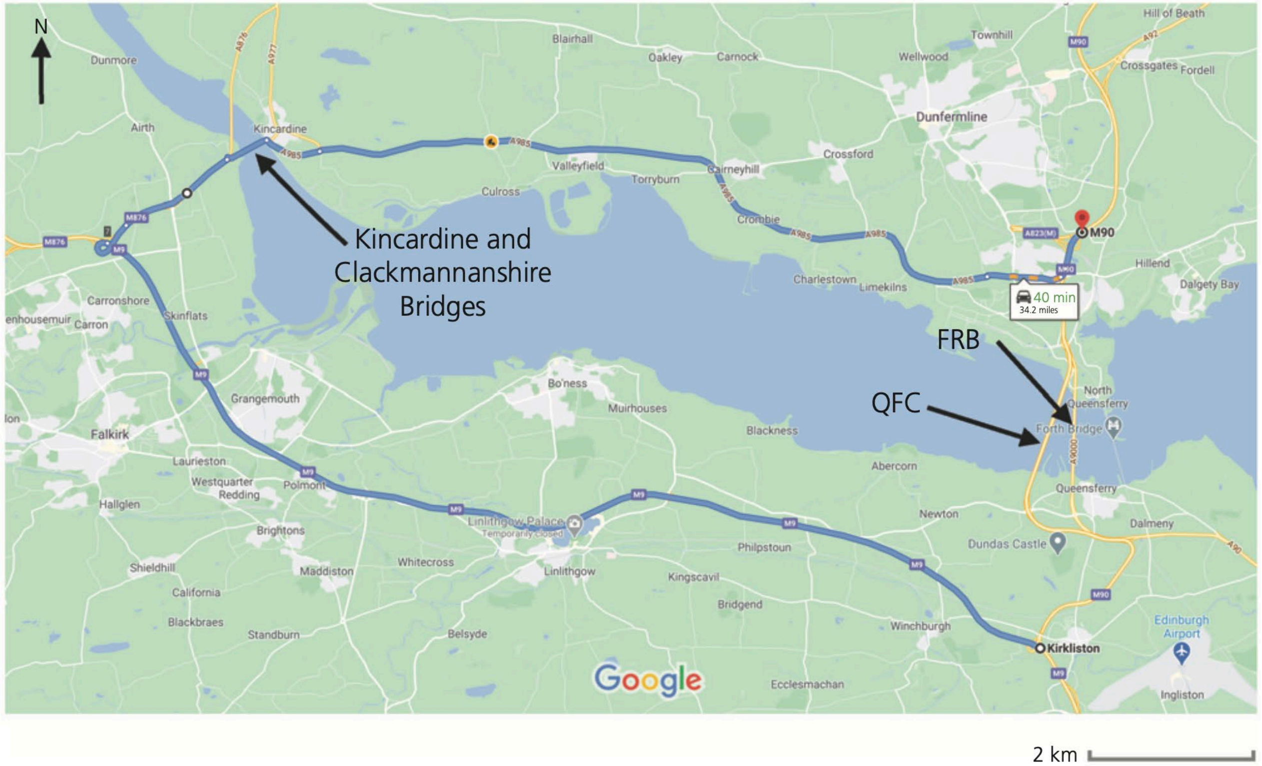
It is the first time the bridge has been closed since it opened to traffic in August 2017

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



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

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

Resilience and sustainability may be correlated or independent

Challenge

Optimisation of climate resilience and sustainability in adaptation

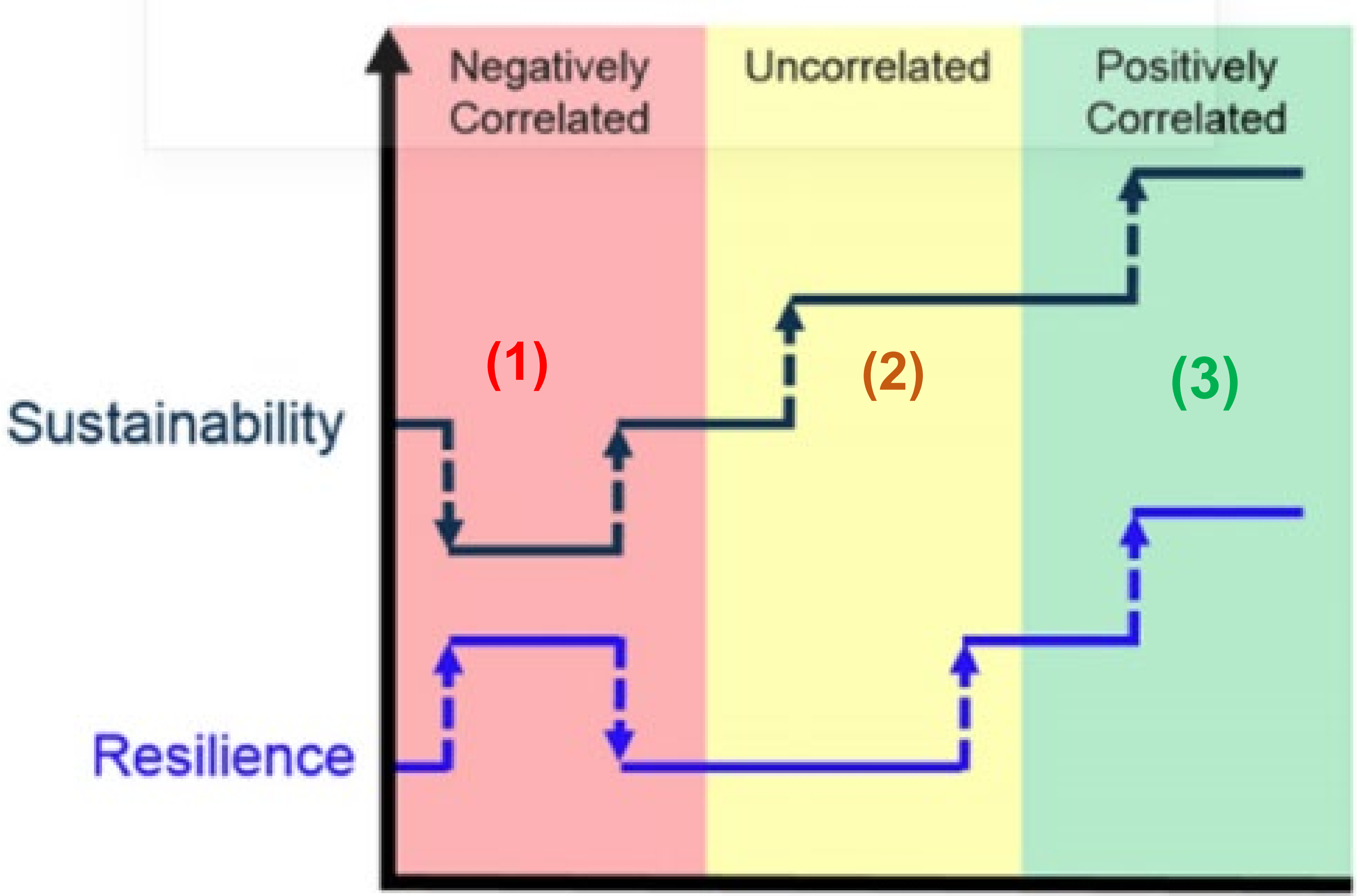
Gap

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

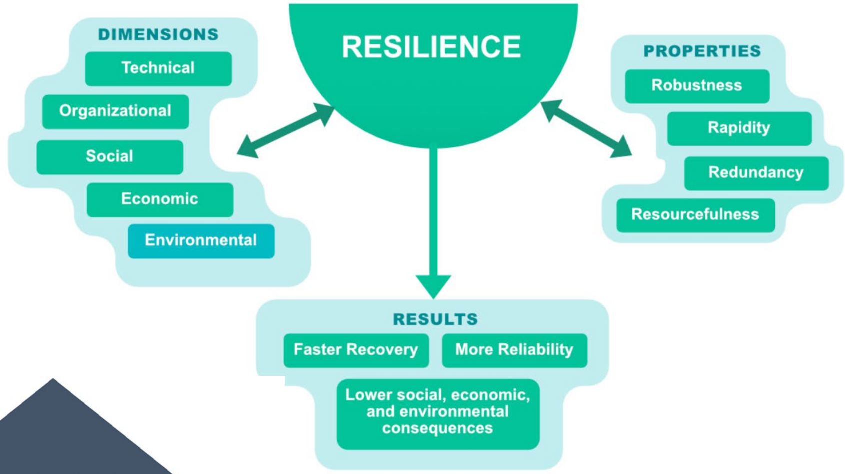
Resilience and sustainability: synergies and competencies

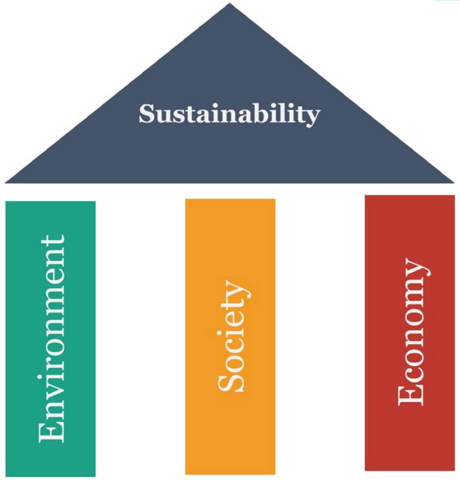


Linkov et al. 2019

Sustainability and resilience can be:

1) **negatively correlated** (competing)
2) **uncorrelated** (not affecting each other) and
3) **positively correlated** (synergistically)

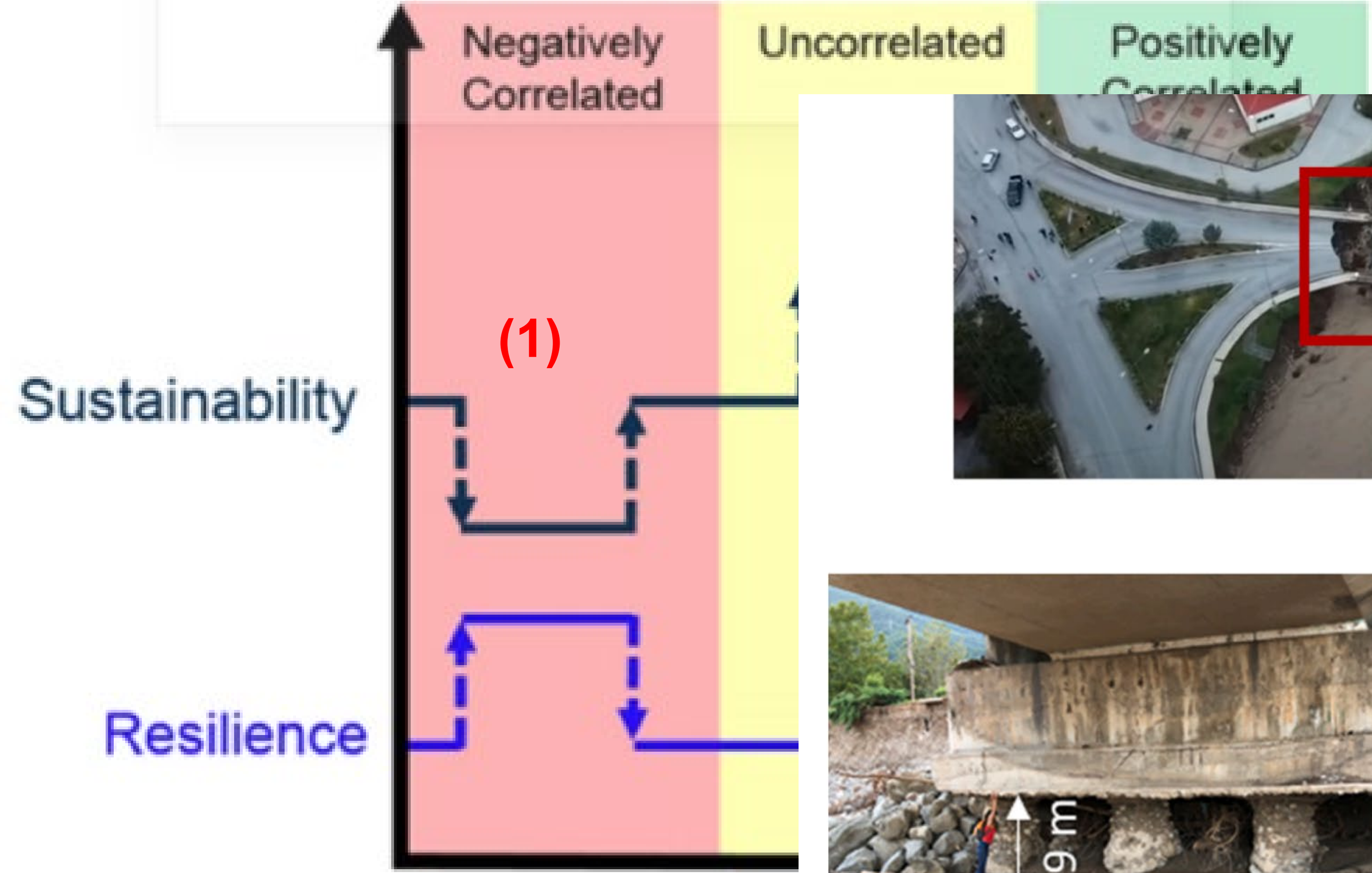




Resilience and sustainability: synergies and competencies

Examples:

1) Restoring a bridge leads to tCO2e (impacts negatively the environment / **Sustainability**) but increases its **Resilience**

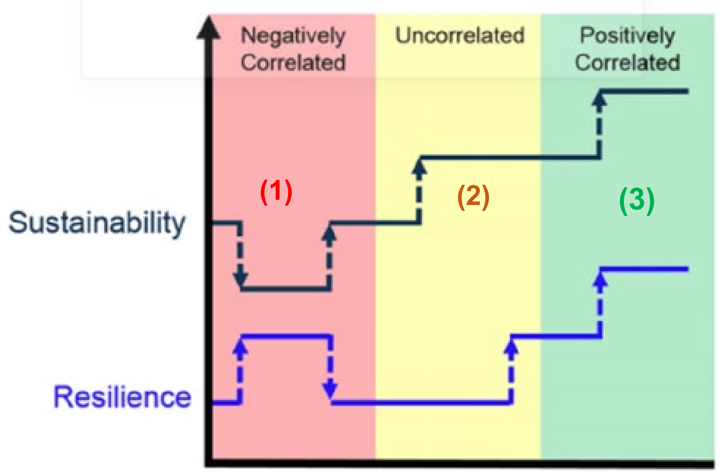


Mitoulis et al. 2021

…but benefits the economy and the society (improves sustainability)

Quantification?

Resilience and sustainability: synergies and competencies



Linkov et al. 2019

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.

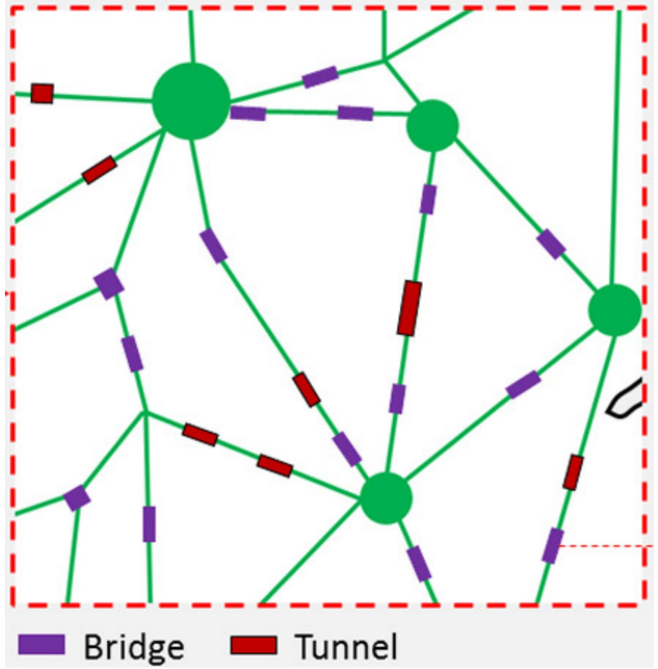
less tCO2e more Sustainable

rip-rap and gabions

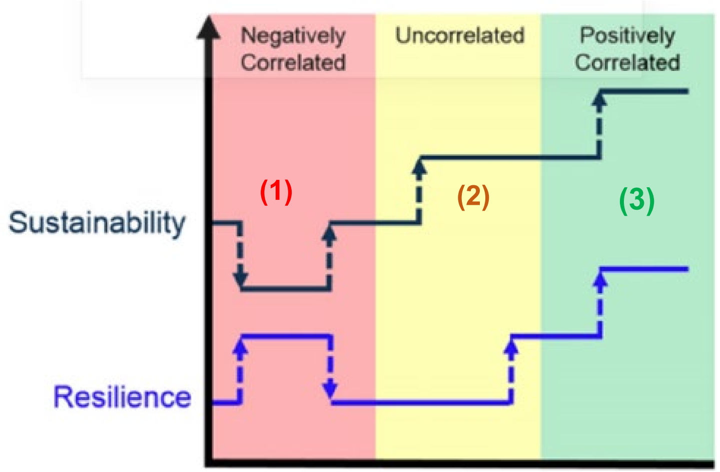
more tCO2e less Sustainable

reinforced concrete

Resilience of network unaffected



Resilience and sustainability: synergies and competencies



Linkov et al. 2019

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

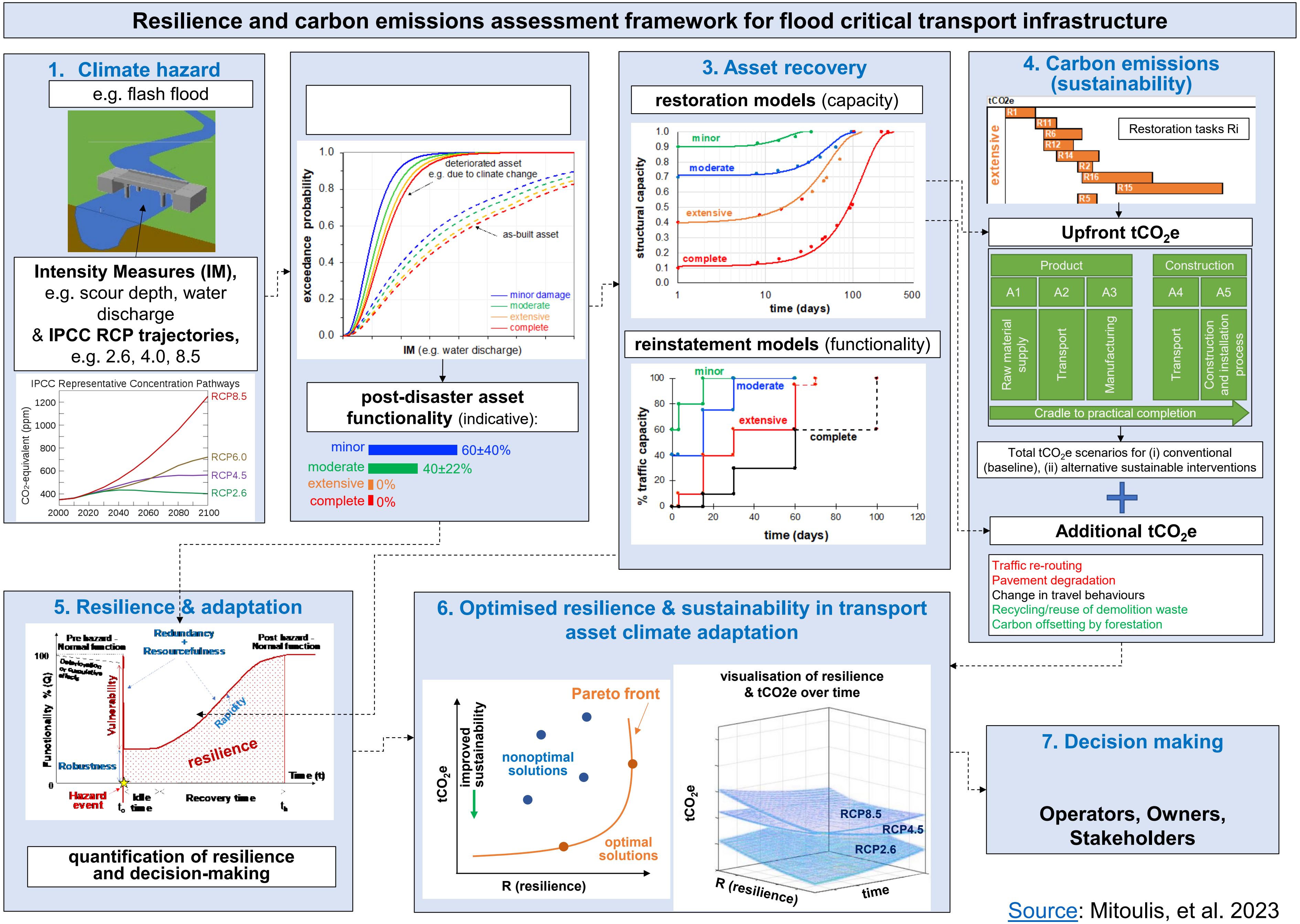
…green is more acceptable by the society (improves sustainability)

but…

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

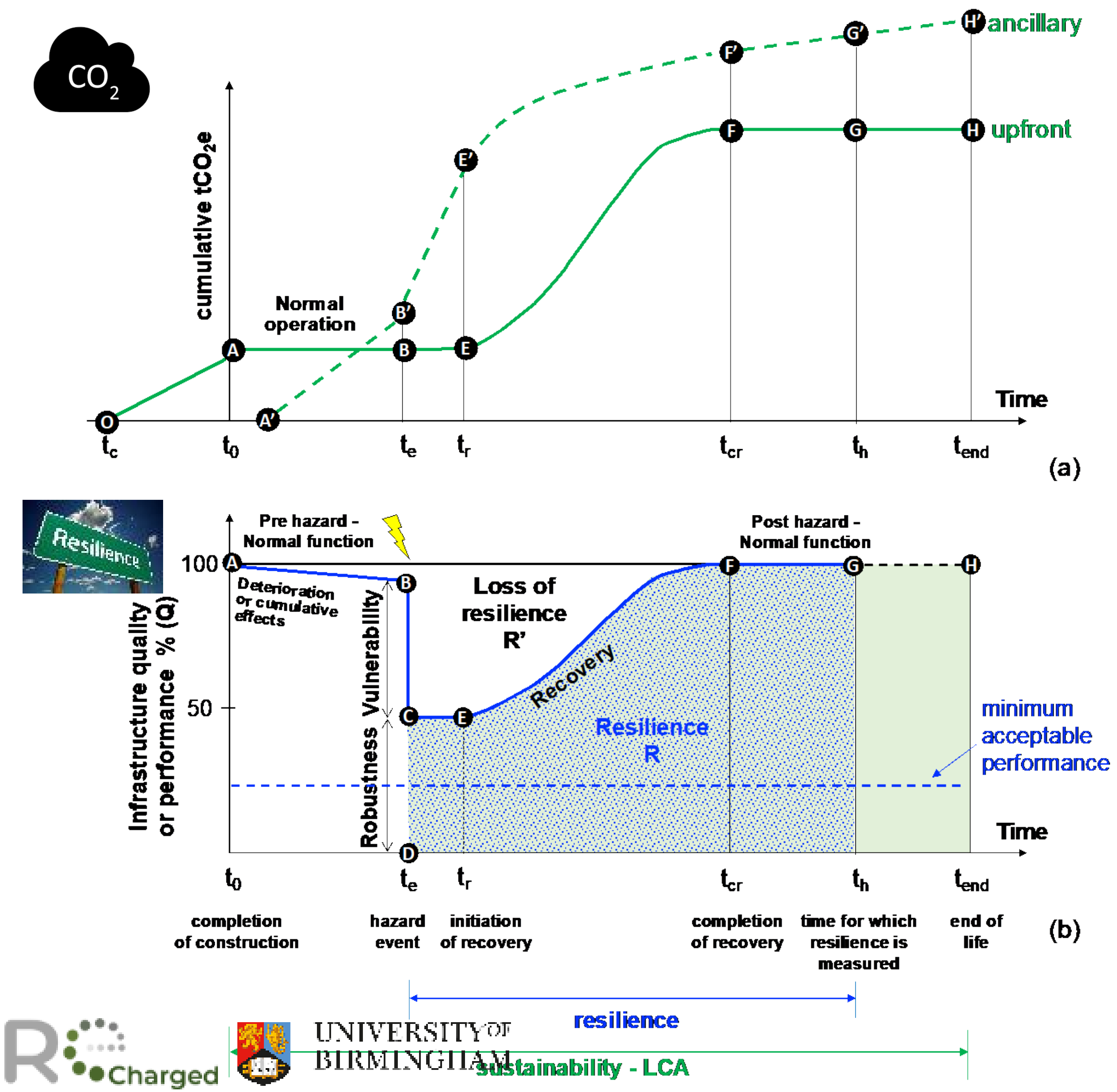
Justice et al. of Presto Geosystems (2020)

Framework for optimising resilience and sustainability



Source: Mitoulis, et al. 2023

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

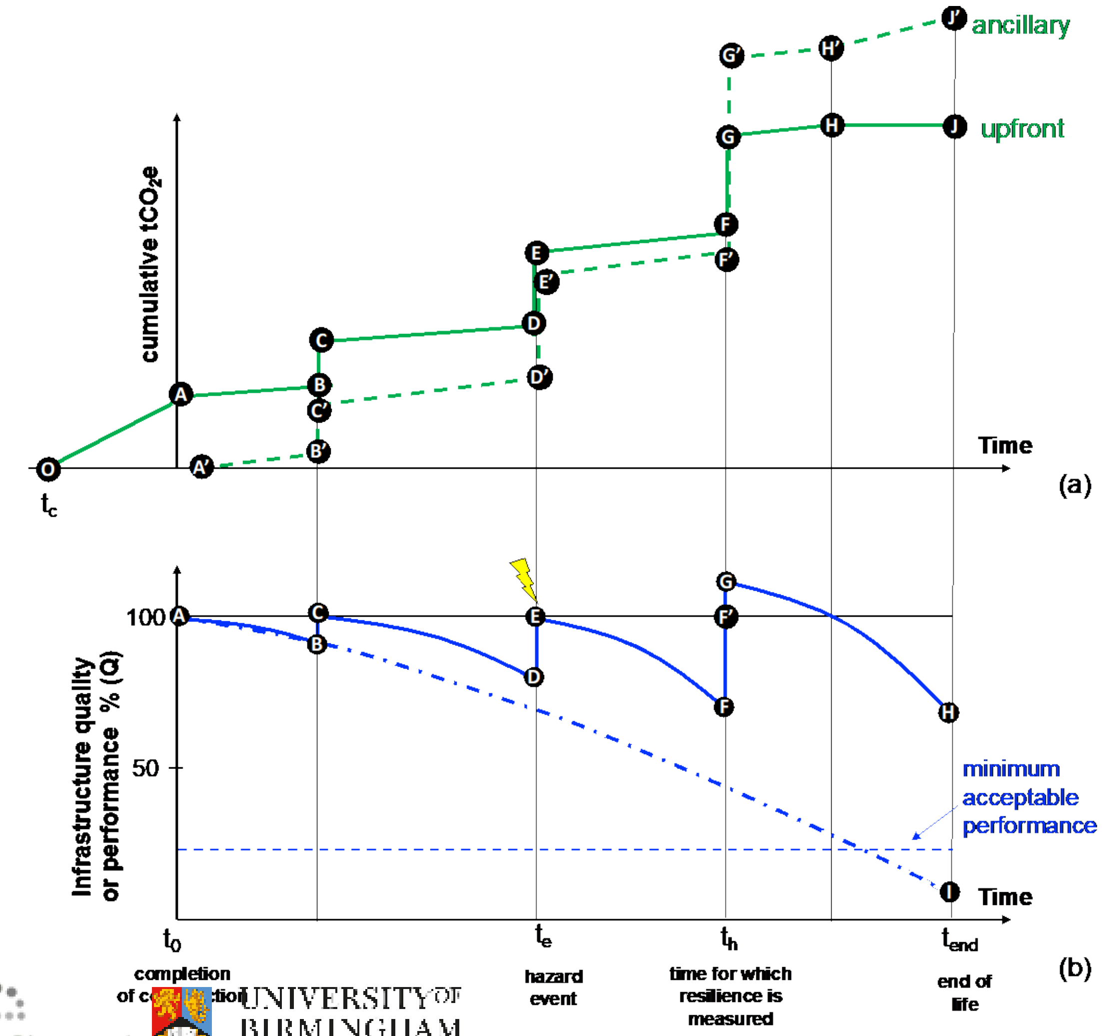
O: commencement of construction,
A: completion of construction, bridge open to traffic
AB: bridge operates with minimal maintenance or inspection
A'B': tCO2e increase because the bridge operates with decreased functionality and as a result vehicle detours are required
BE: bridge is damaged, but no action 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

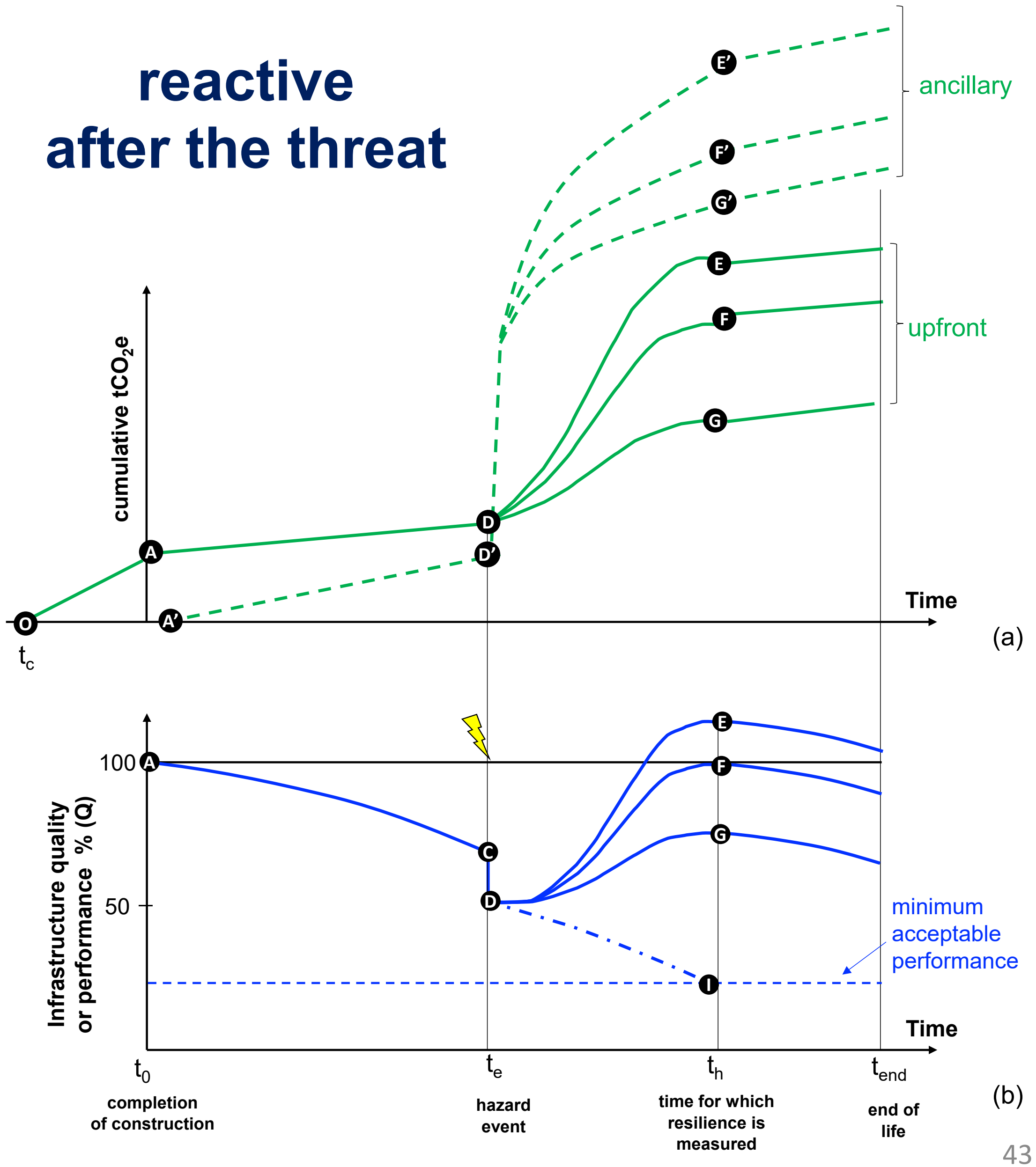
Case study on optimising resilience and sustainability metrics

Proactive vs reactive adaptation strategies

proactive before the threat



reactive after the threat



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

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

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

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

tCO2e

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

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

Sustainability metric

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

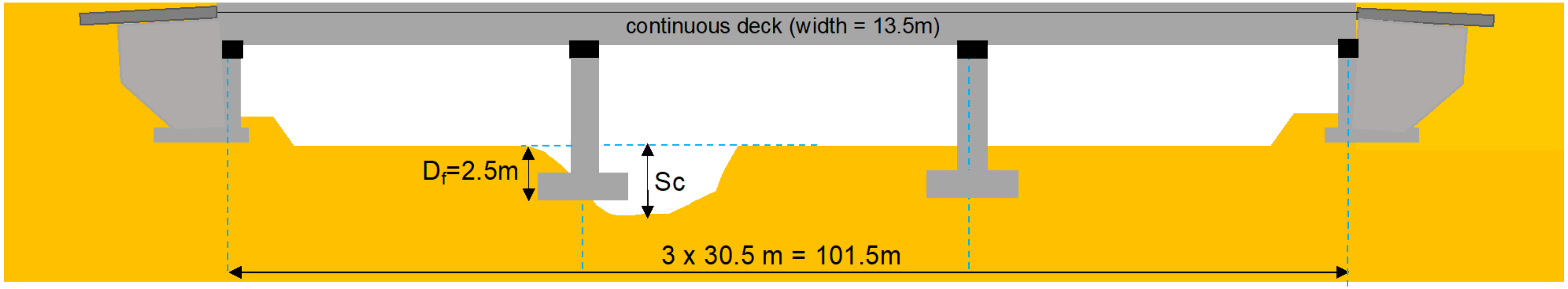
Cost metric

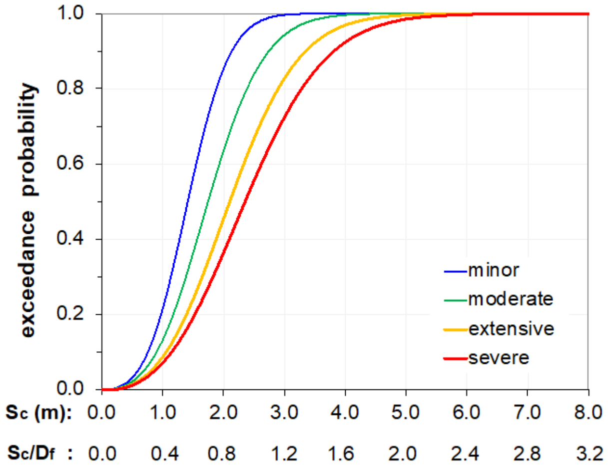
$$C_j=\frac{C_j(T=t_h)}{max(C)}$$

Global metric

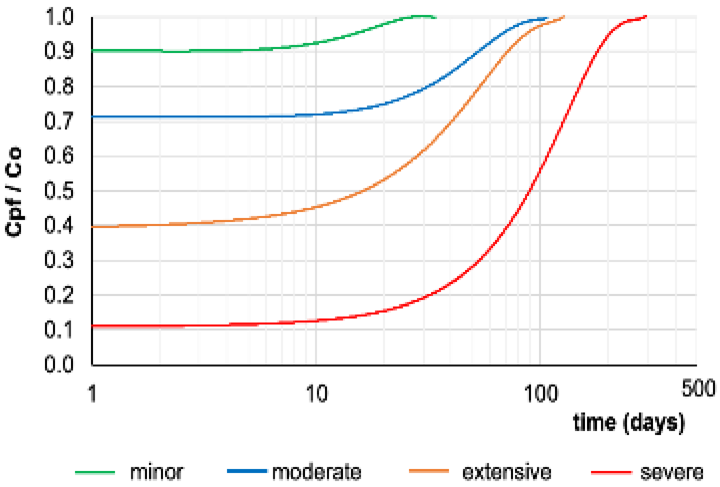
$$I_{SRC,j}=\gamma_S \cdot S_j \cdot \frac{\gamma_R \cdot R_j}{\gamma_C \cdot C_j}$$

Case study on optimising resilience and sustainability metrics



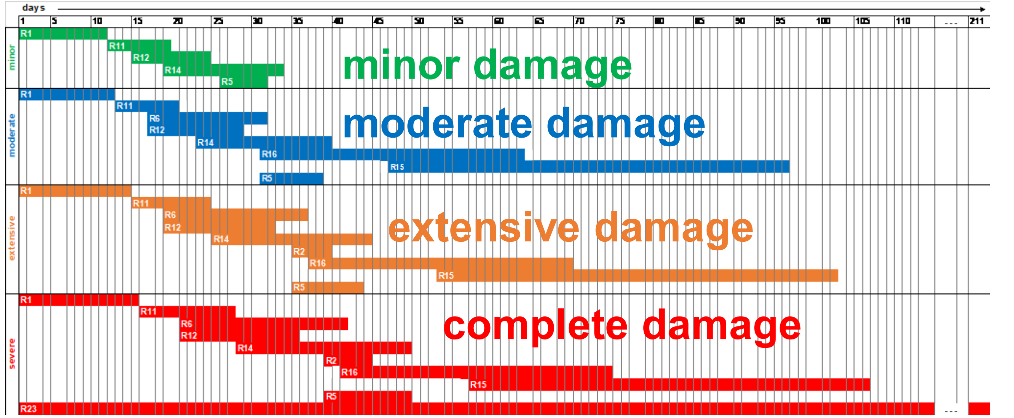


fragility
damage probability vs flood intensity



restoration
Capacity/performance gain vs time

Restoration task durations & tCO2e



		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	1.6	2.4	0.1	4.1	-9.2	±29.8

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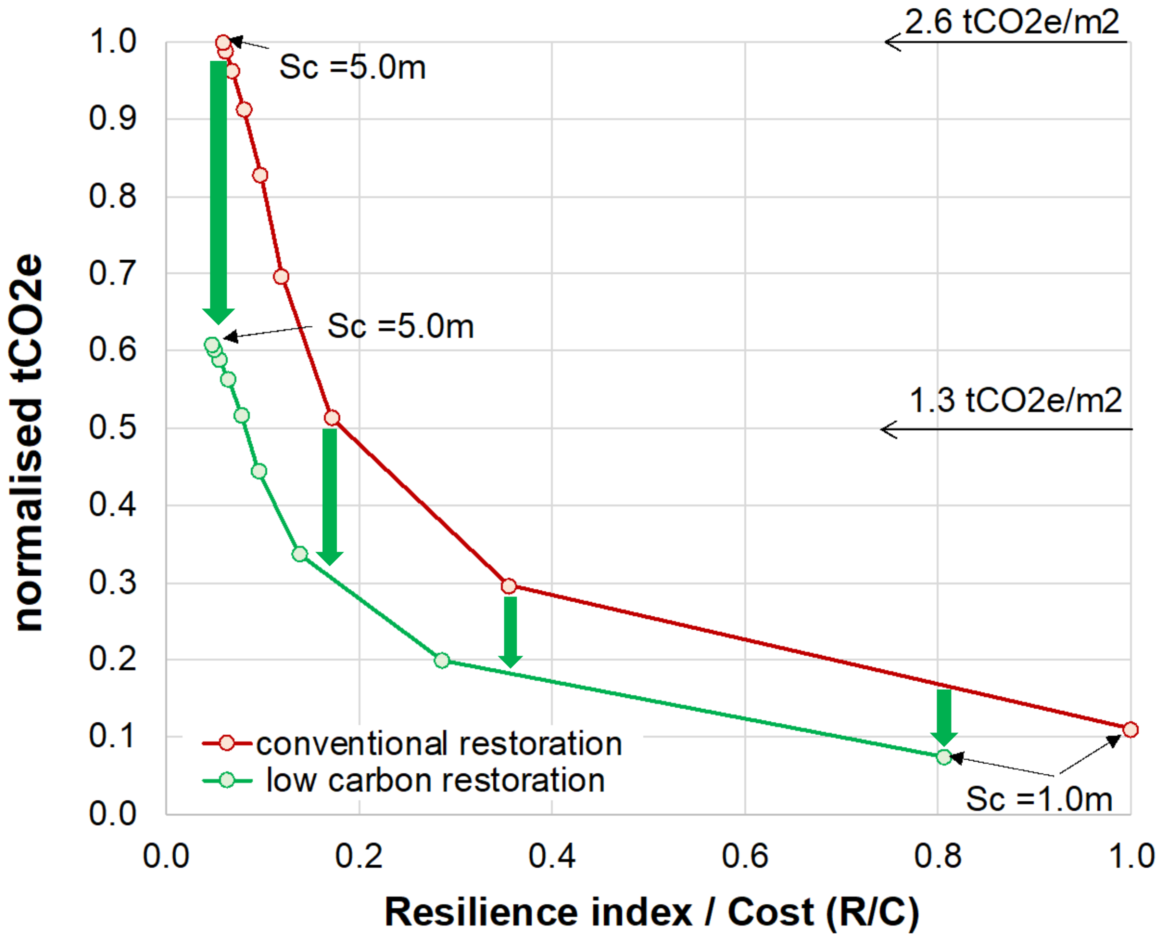
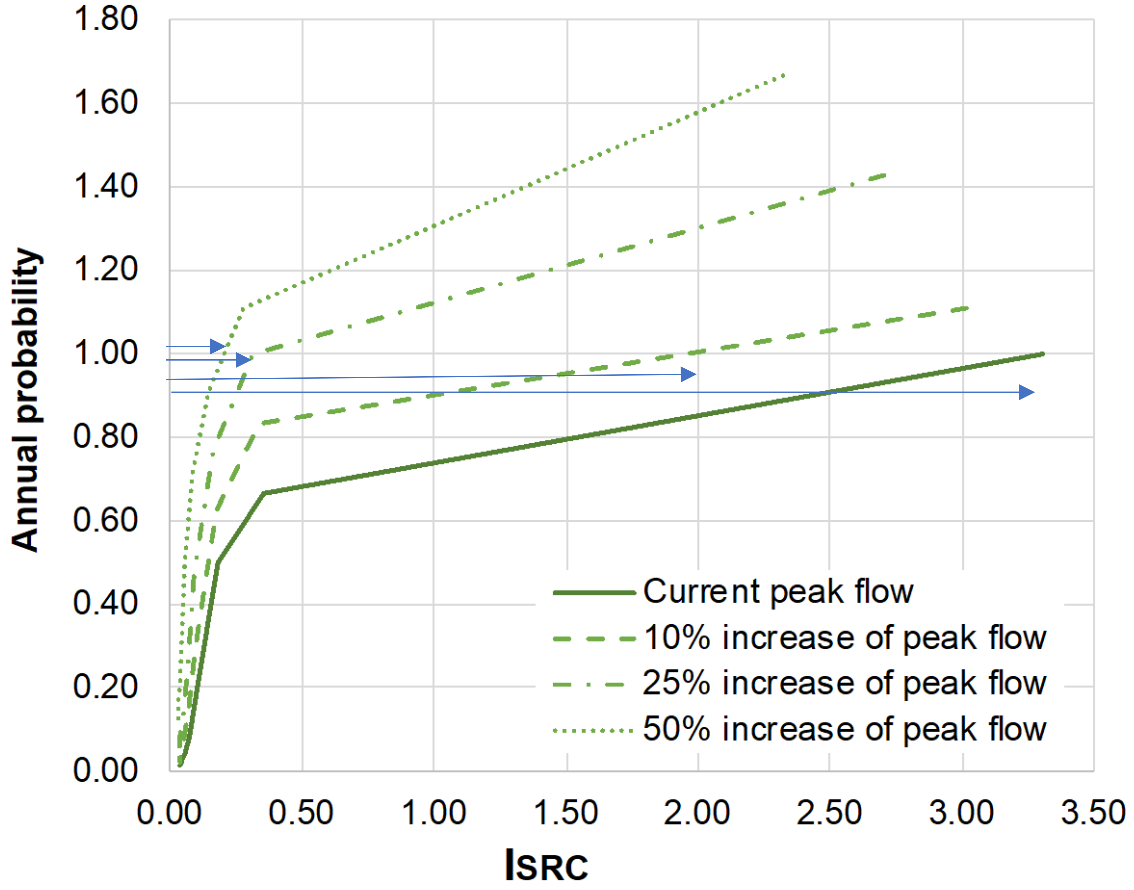
Results- Quantification of S,R,C





Source: Mitoulis, et al. 2023

γ_s, γ_R and γ_C are weighting factors which the decision maker can adjust to prioritise e.g., **S**ustainability, **R**esilience or **C**ost.

$$I_{SRC,j} = \gamma_S \cdot S_j \cdot \frac{\gamma_R \cdot R_j}{\gamma_C \cdot C_j}$$

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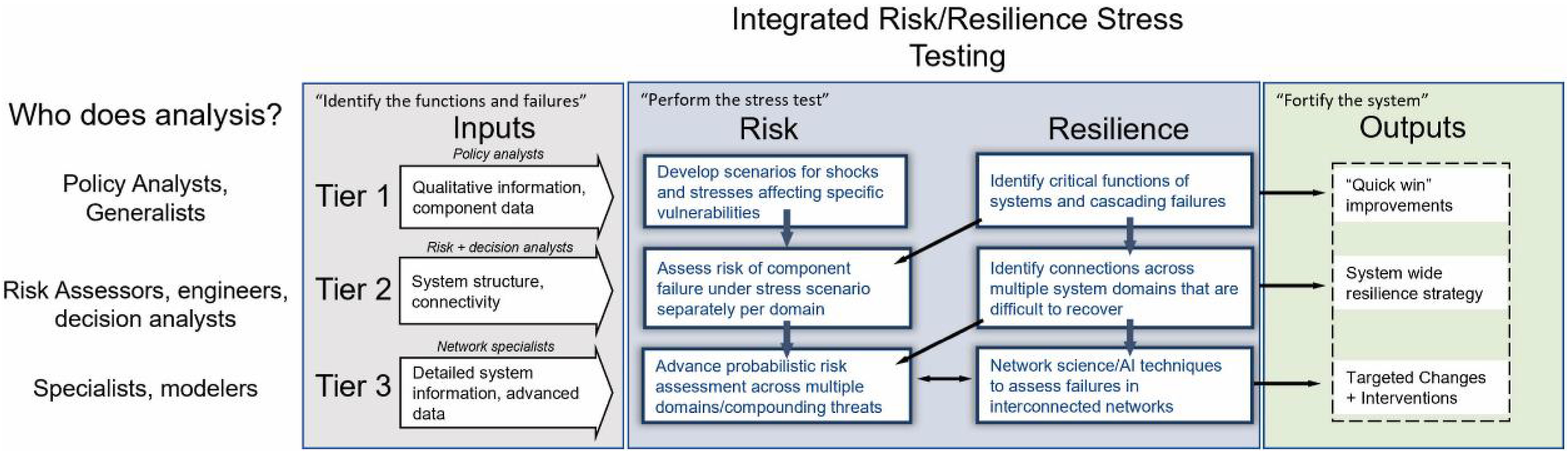
Discussion points

Threat-agnostic resilience *based on stress-testing resilience*



Linkov et al., 2022