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

Lecture 3 Resilience assessment

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

Lecture 3-Week 3
The aim of this week is to introduce the concept and properties of resilience for critical infrastructure, including quantification of resilience based on metrics for decision making. This week also includes definition of restoration and reinstatement models considering available resources, level of damage and type of infrastructure assets. The concepts of proactive (ex-ante / by design) and reactive (ex-post/ by intervention) resilience will be presented based on case studies for critical assets. Resilience by assessment will be discussed as a capability in case of inaccessible assets.

- Define resilience and its properties, restoration and reinstatement models, considering temporal and spatial variabilities.
- Define proactive and reactive restoration at asset and system level.
- Define resilience metrics for decision-making.

Present case studies on quantification of resilience for critical infrastructure exposed to different hazard scenarios.

Lecture 3. Resilience assessment

Lecture 3
Massive Open Online Course
Resilience, Sustainability & Digitalisation in Critical Infrastructure

Resilience assessment

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Lecture 3 Outcomes

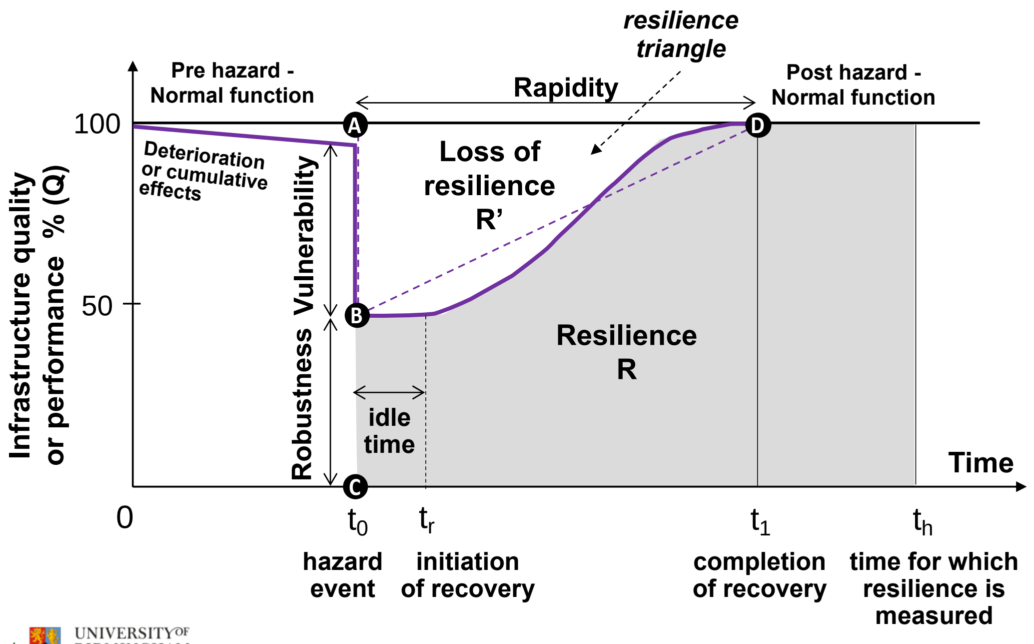
- Define resilience and its properties, restoration and reinstatement models, considering temporal and spatial variabilities.
- Define proactive and reactive restoration at asset and system level.
- Define resilience metrics for decision-making.
- Present case studies on quantification of resilience for critical infrastructure exposed to different hazard scenarios.

Activity 1. Restoration and reinstatement models

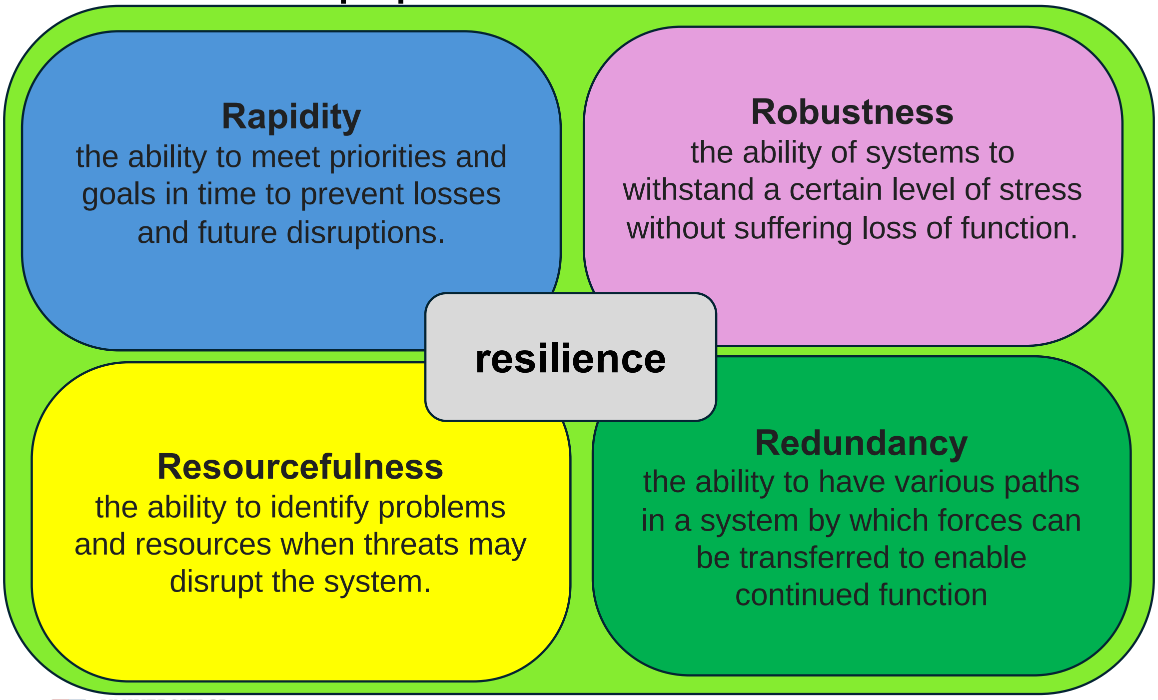
ACTIVITY 1: Restoration and reinstatement models

- Define resilience and its properties
- Restoration and reinstatement models
- Restoration vs reinstatement
- Temporal and spatial variabilities and other uncertainties

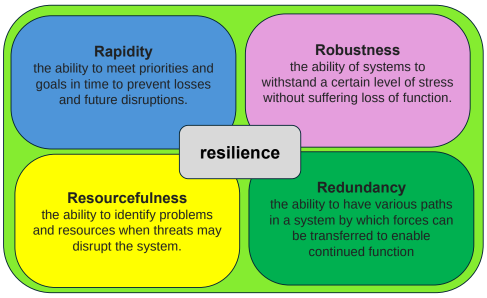
Resilience assessment

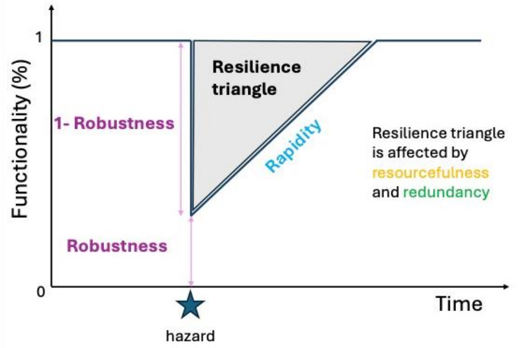


Define resilience and its properties



The attributed of resilience - the 4Rs (Bruneau et al. 2003)





Different scales: from micro-to macro scale

Bottom-up approach:

component → asset → network→ system→ system of systems→ regional → national → international

Top-down approach:

international → national → regional → system of systems → system → network → asset → component

Restoration and reinstatement models

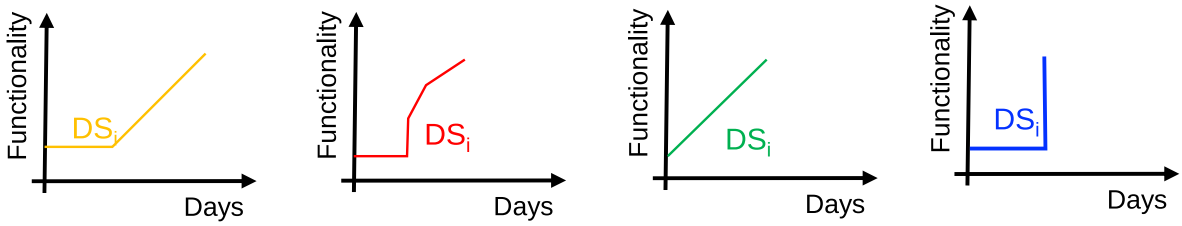
Quantification of resilience

robustness of structure, rapidity of restoration, resilience indices, examples

Resilience: the capacity to recover quickly from catastrophic events.

Usually **recovery functions** are defined for different hazards and damage states, and thus combined to derive the **resilience curve** of a structural system.

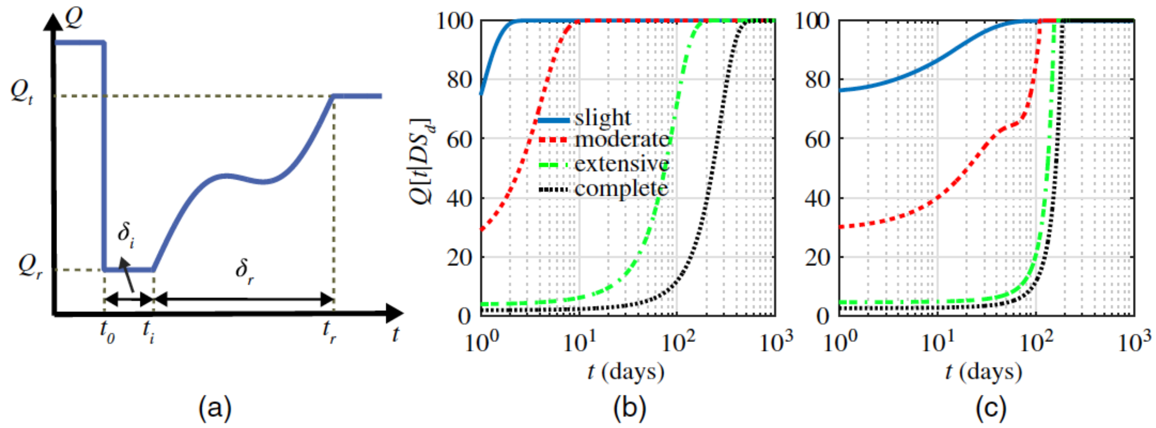
Different **functional forms** can be adopted to characterise recovery functions.



… or continuous functional forms usually representative of cumulative probability density function. This is convenient since it allows characterising recovery only defining few parameters.

Restoration and reinstatement models

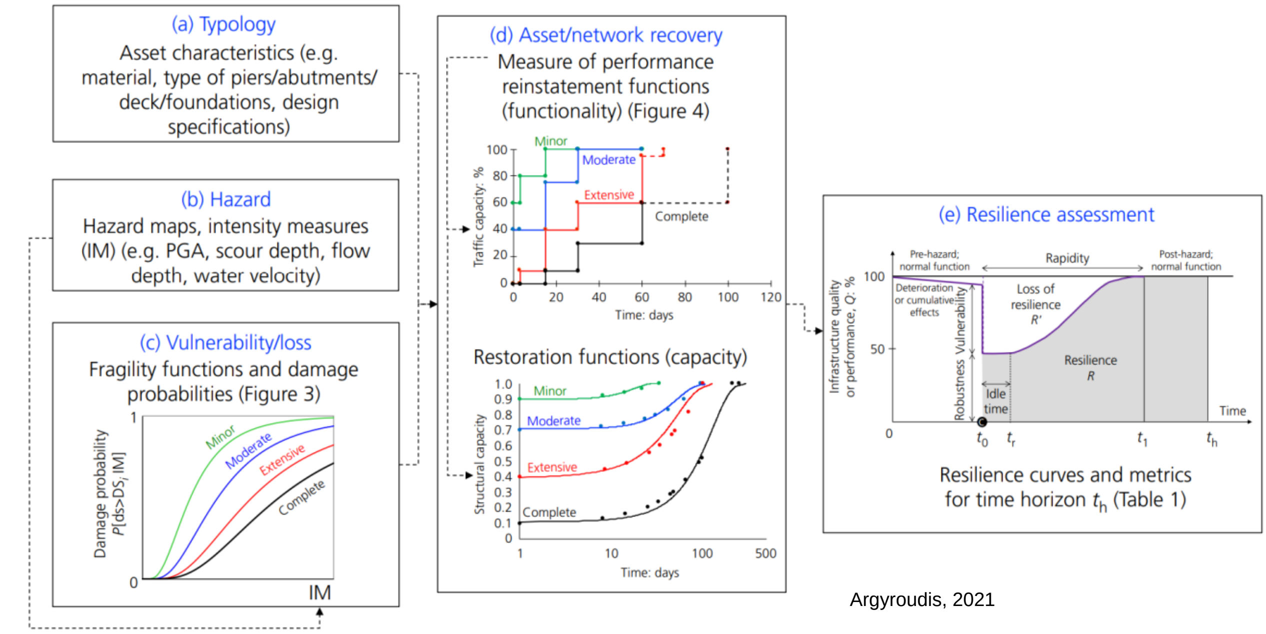
Restoration curves



(a) illustration of functionality recovery process
(b) Hazus (2011)
(c) Multi-parameter sinusoidal model (Bocchini et al.)

4R : Robustness, Redundancy, Resourcefulness, Rapidity

Restoration and reinstatement models



Argyroudis, 2021

Restoration vs reinstatement

Survey for bridge restoration after flood

damage level (DL) *(see Table 1 for description)*	idle time in days (before any restoration works)		reinstatement time in days (after the initiation of the restoration works)															restoration tasks & prioritisation *(see Table 3)*	cost ratio *(% of replacement cost of the bridge)*
			0			3			15			30			60				
	min	max	% traffic capacity of the bridge after damage																
(1)	(2)	(3)	(4) *(check mark "X")*															(5)	(6)
			0	50	100	0	50	100	0	50	100	0	50	100	0	50	100		
minor	4	14		X				X			X			X			X	R12, R5	5
moderate	10	30	X			X				X				X			X	R1, R12, R5	8
extensive	25	45	X			X			X					X			X	R1, R6, R12, R14, R2, R16, R5	15
severe	30	70	X			X			X			X					X	R1, R6, R12, R14, R2, R16, R15, R5	30
comments:																			

Mitoulis SA, et al. 2021

Restoration vs reinstatement

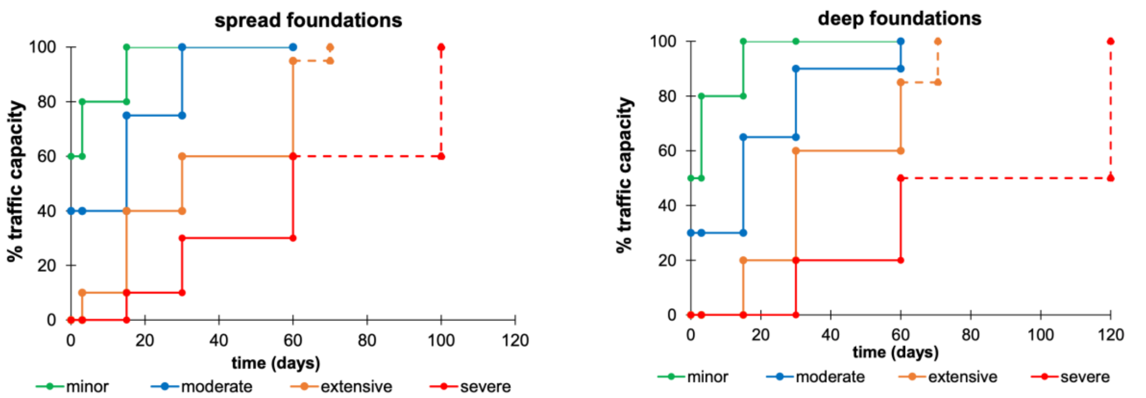
Survey results and processing

code	restoration task	duration (days)				weighting factors			
		minimum	maximum	mean	std dev	minor	moderate	extensive	severe
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
R0	no action is required	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*
R1	armouring countermeasures and flow-altering/cofferdam	5.6	24.8	15.2	13.4	0.7	0.8	0.9	1.0
R2	temporary support per pier	3.2	9.2	6.2	4.2	0.7	0.8	0.9	1.0
R3	temporary support of one abutment	3.0	10.0	6.5	4.6	0.7	0.8	0.9	1.0
R4	temporary support of one deck span /segment (midspan or support)	3.6	10.8	7.2	3.9	0.7	0.8	0.9	1.0
R5	repair cracks and spalling with epoxy and/or concrete	3.4	19.0	11.2	13.0	0.5	0.7	0.85	1.0
R6	re-alignment and/or leveling of pier	12.0	29.8	20.9	23.6	0.5	0.7	0.85	1.0
R7	re-alignment of bearings	2.8	10.0	6.4	6.8	1.0	1.0	1.0	1.0
R8	jacketing or local strengthening (pier or abutment or foundation)	11.4	35.0	23.2	30.0	0.0	0.4	0.7	1.0
R9	jacketing or local strengthening (deck)	13.8	32.8	23.3	23.3	0.0	0.4	0.7	1.0
R10	re-alignment of deck segment	8.2	18.2	13.2	17.9	0.5	0.7	0.85	1.0
R11	erosion protection measures	6.8	16.3	11.5	6.4	0.7	0.8	0.9	1.0
R12	rip-rap and/or gabions for filling of scour hole and scour protection	6.0	23.4	14.7	13.5	0.7	0.8	0.9	1.0
R13	removal of debris	2.9	7.4	5.2	4.7	0.7	0.8	0.9	1.0
R14	ground improvement per foundation	11.2	32.0	21.6	21.8	0.7	0.8	0.9	1.0
R15	installation or retrofitting of deep foundation system	33.8	66.0	49.9	49.3	1.0	1.0	1.0	1.0
R16	extension of foundation footing	20.8	46.0	33.4	32.1	1.0	1.0	1.0	1.0
R17	reconstruction/replacement of the abutment and wingwalls	31.0	72.0	51.5	41.1	1.0	1.0	1.0	1.0
R18	reconstruction/replacement of the pier	42.0	78.0	60.0	44.3	1.0	1.0	1.0	1.0
R19	temporary support and replacement of the bearings	3.8	9.4	6.6	3.8	1.0	1.0	1.0	1.0
R20	replacement of the backfill and approach slab and mudjacking	12.0	32.0	22.0	11.5	1.0	1.0	1.0	1.0
R21	replacement of expansion joint	2.0	7.2	4.6	3.1	0.5	0.7	0.85	1.0
R22	demolish/replacement of a deck span/segment	22.2	51.0	36.6	23.2	1.0	1.0	1.0	1.0
R23	demolish/replacement (part) of the bridge	88.8	334.0	211.4	133.8	1.0	1.0	1.0	1.0
R24	*please add customised task*	-	-	-	-	-	-	-	-

ReCharged UNIVERSITY OF BIRMINGHAM Mitoulis et al. 2021

Restoration vs reinstatement

Survey results: reinstatement models



(a) (b)

Figure 3. Reinstatement models illustrating the post-flood gain of the traffic capacity (%) of the bridge for spread (a) and deep (b) foundation (dashed lines is a projection based on judgment).

Mitoulis et al. 2021

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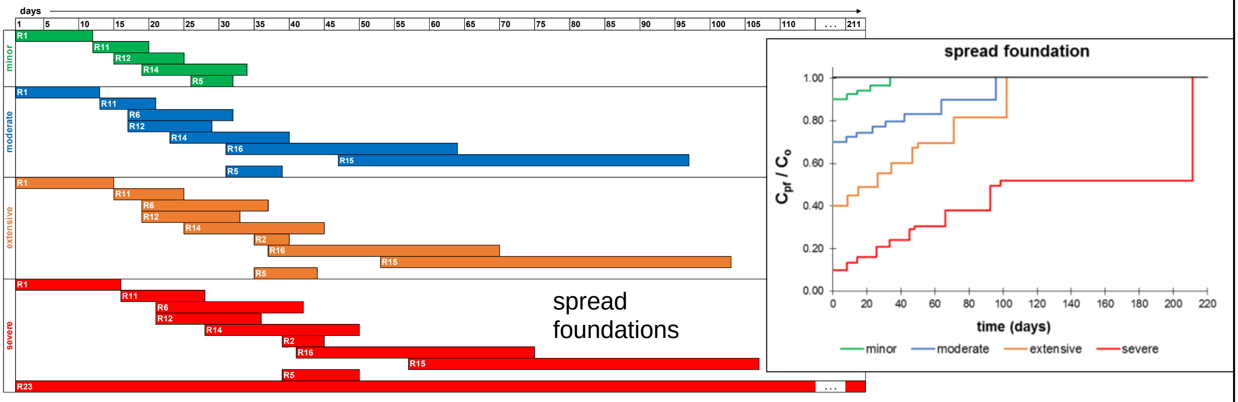
Restoration vs reinstatement

Restoration task prioritisation, dependencies, durations & models



Stepwise restoration models illustrating the ratio of the post-flood bridge capacity (C_{pf}) over the original capacity (C_o)

Mitoulis et al. 2021

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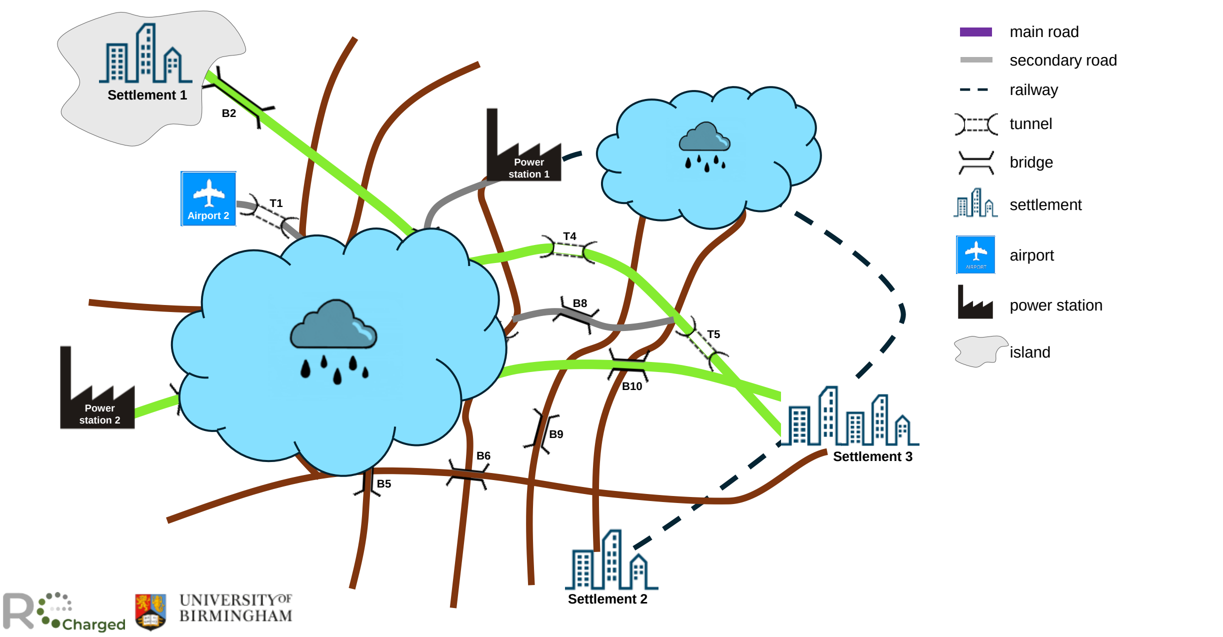
Temporal and spatial variabilities and other uncertainties



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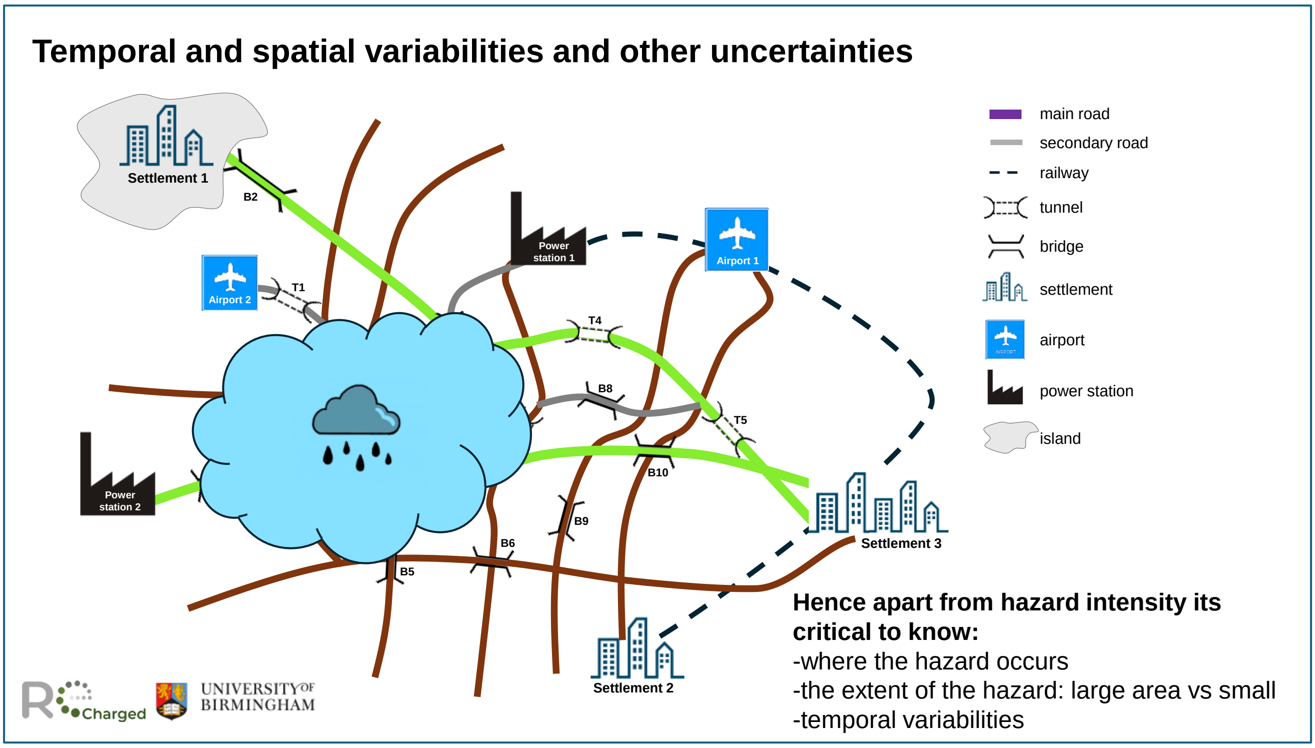

The two slides above illustrate conceptual maps highlighting the importance of understanding temporal and spatial variabilities and other uncertainties related to hazards for our resilience assessments.

Components of the Map:

1. **Routes and Infrastructure:**
   - **Main Roads:** Indicated by thick purple lines.
   - **Secondary Roads:** Represented by thinner gray lines.
   - **Railways:** Depicted by dashed lines.
   - **Tunnels:** Shown as connected double lines (T1, T4, T5).
   - **Bridges:** Represented by parallel lines with a gap (B2, B5, B6, B8, B9, B10).
2. **Key Locations:**
   - **Settlements:** Illustrated with building icons and labelled as Settlement 1, Settlement 2, and Settlement 3.
   - **Airports:** Depicted with airplane icons and labelled as Airport 1 and Airport 2.
   - **Power Stations:** Represented with factory icons and labelled as Power station 1 and Power station 2.
   - **Island:** Shown as a landmass shape.
3. **Hazard Representation:**
   - Cloud with raindrops symbolizing a hazard event affecting the area, placed centrally on the map.

Points of Interest:

- The green lines appear to denote critical routes or pathways impacted by the hazard.
- The connections between different infrastructures (e.g., roads, railways, bridges, tunnels) suggest a complex network affected by the hazard.

- The description emphasizes the importance of knowing:
    - **Where the hazard occurs**
    - **The extent of the hazard (large area vs. small area)**
    - **Temporal variabilities (time-related changes)**

This map serves to emphasize the necessity of understanding the spatial distribution and temporal aspects of hazards, focusing on how they impact various infrastructural elements and settlements. It highlights the interconnected nature of these elements and the critical information required to manage and mitigate hazards effectively.

Activity 2. Proactive and reactive restoration

ACTIVITY 2: Proactive and reactive restoration

- Proactive (ex-ante) vs. reactive (ex-post) and comparisons strategies
- Adaptation strategies

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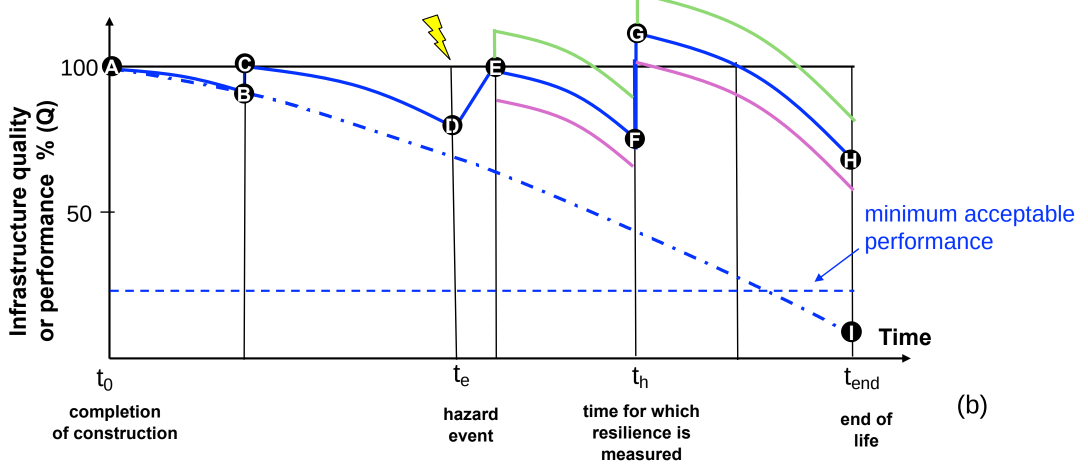
Proactive (ex-ante) vs. reactive (ex-post) and comparisons strategies

Proactive / preventive maintenance / adaptation before the threat



AI: deterioration of infrastructure quality throughout its life
BC: proactive adaptation measures and/or maintenance
CD: deterioration of infrastructure
DE: restoration after a climate hazard occurrence (see Fig. 1, C to F)
FG: enhancement of infrastructure performance with adaptation measures
GH: operation until the end of life

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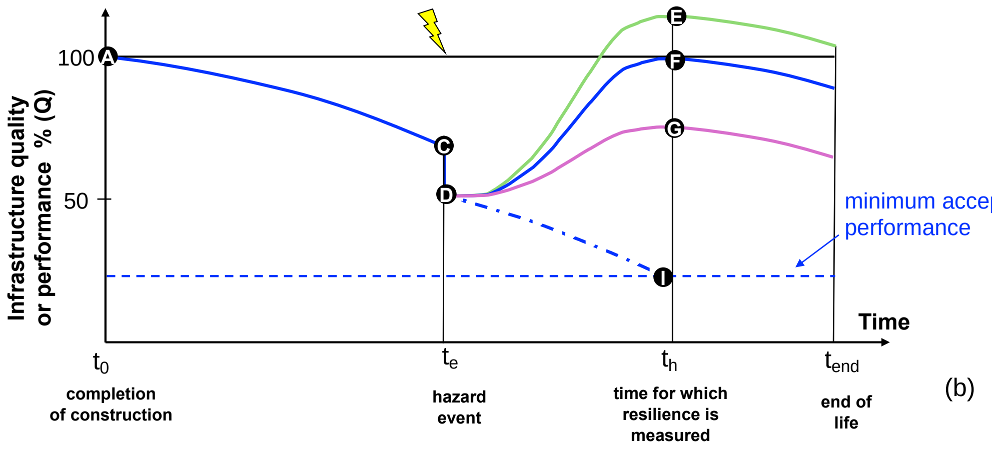
Proactive (ex-ante) vs. reactive (ex-post) and comparisons strategies

Reactive / corrective maintenance/adaptation before the threat



AI: deterioration of infrastructure quality throughout its life
CD: loss of performance due to hazard occurrence
DG: reactive measures, partially restored
DF: reactive measures, fully restored
DE: reactive and adaptation measures beyond the original capacity

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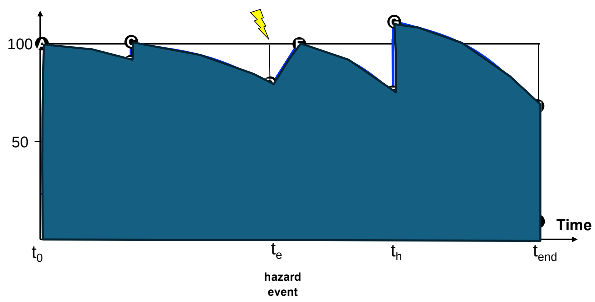
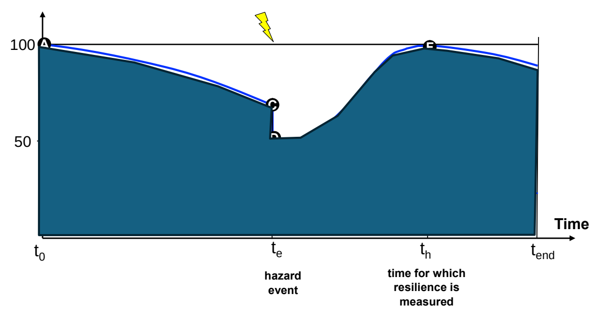
Proactive (ex-ante) vs. reactive (ex-post) and comparisons strategies





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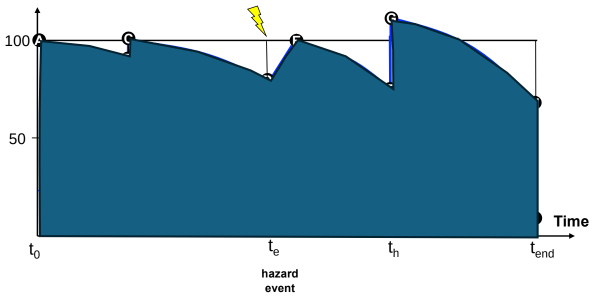
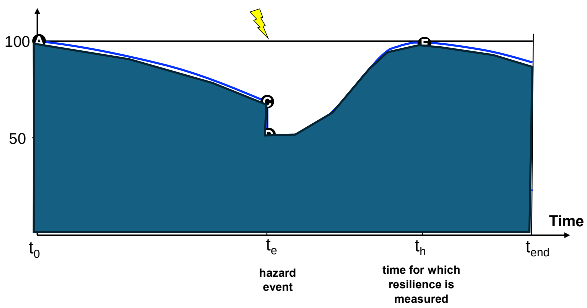
Proactive (ex-ante) vs. reactive (ex-post) and comparisons strategies





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Adaptation strategies

EU Strategy on Adaptation to Climate Change - Policy context

- The **2030 Agenda for Sustainable Development**
- The **Paris Agreement**
- The **European Green Deal**:
  - European **Climate Law,**
  - **2030 Climate** Target Plan
  - European **Climate Pact**
  - EU **Biodiversity** strategy
  - **Farm to fork** strategy
  - **Forest** strategy
  - Renewed **sustainable finance** strategy
  - … and more!

European Commission

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Adaptation strategies

EU Strategy on Adaptation to Climate Change - Vision & Objectives

- Vision: by 2050 the EU will be a climate-resilient society, fully adapted to the unavoidable impacts of climate change
- Objectives:
  - **Smarter adaptation** – improving knowledge and managing uncertainty
  - **More systemic adaptation** – support policy development at all levels and sectors
  - **Faster adaptation** – speeding up adaptation across the board
  - **Stepping up international action** for climate resilience

© picture: Peter Löffler

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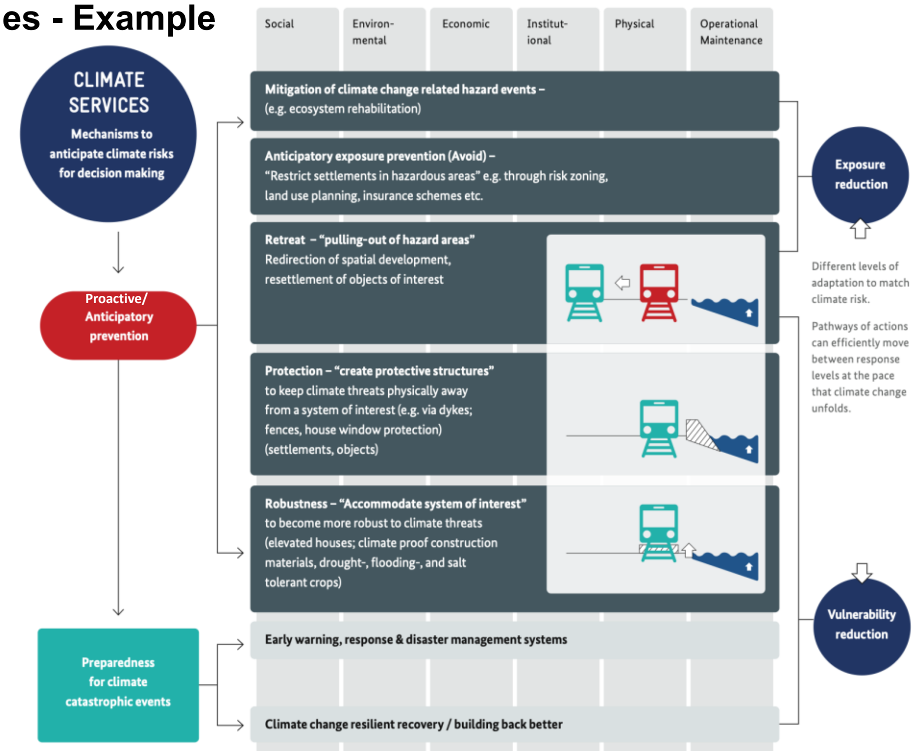
European Commission

Adaptation strategies - Example

Climate risk management approaches at different levels of climate change



source: https://www.transformative-mobility.org

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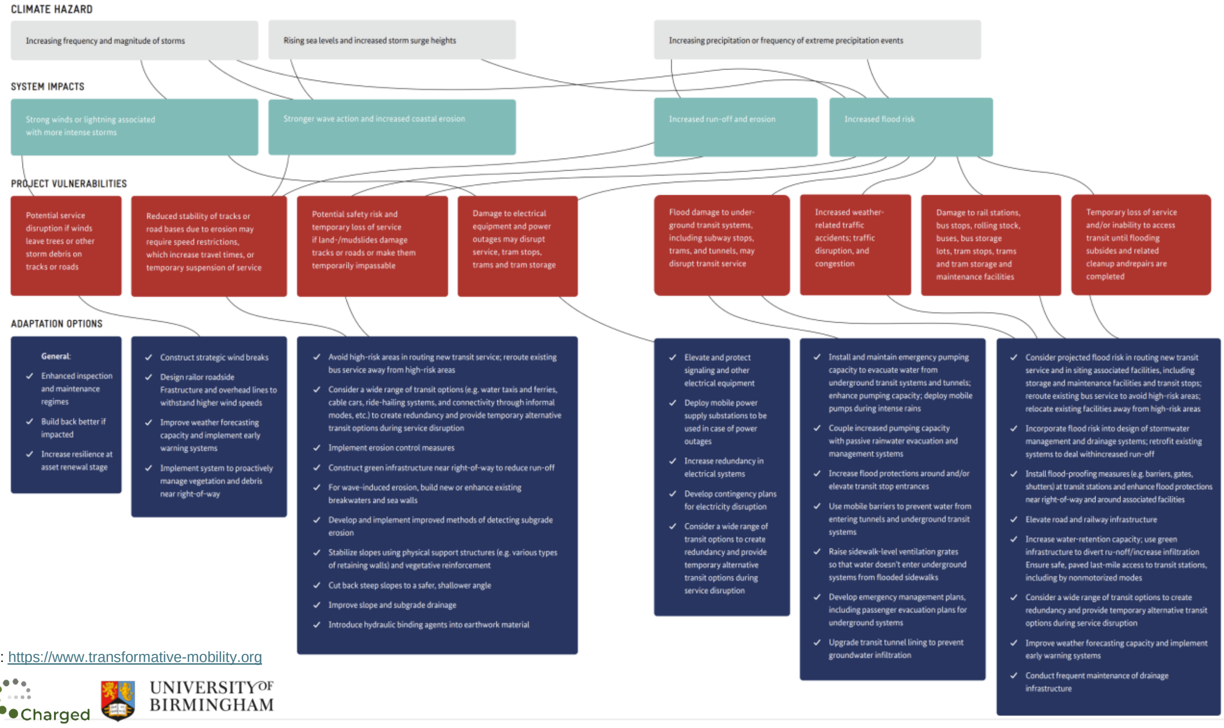
Adaptation strategies - Decision tree for urban mass transit projects



source: https://www.transformative-mobility.org

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Comparisons of ex-ante and ex-post strategies

Discussion:

- Can you think of qualitative examples where proactive strategies would be more efficient and cost effective to reactive strategies?

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Activity 3. Resilience metrics

ACTIVITY 3: Resilience metrics

- Resilience metrics
- Resilience-based decision making
- Case studies

Resilience metrics

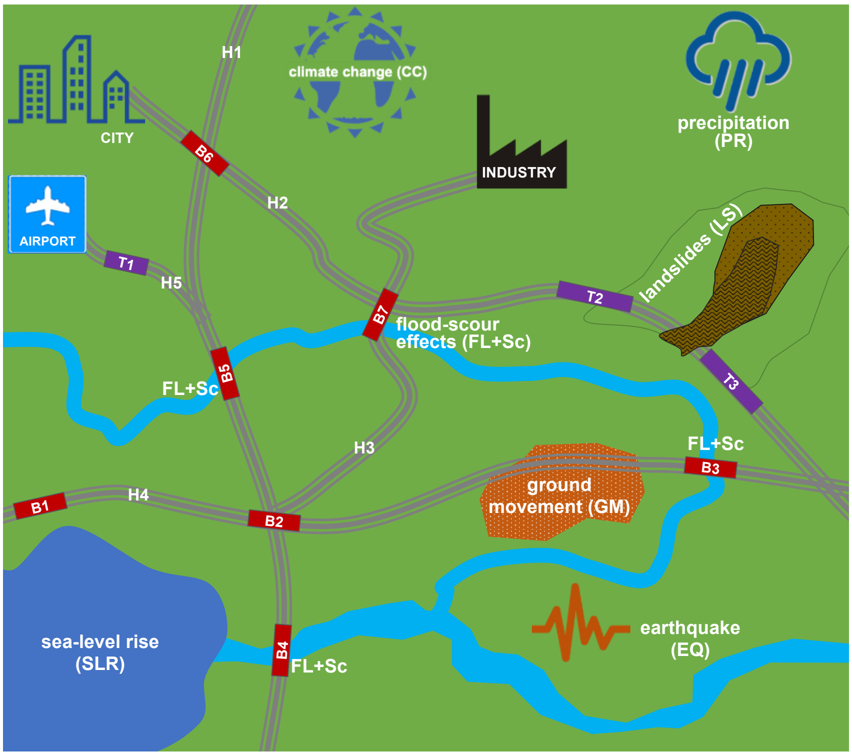


Figure 1: Resilience model

Resilience metrics

reference	mathematical formulation	parameters of the resilience metric	comments and/or advantages & disadvantages
Ayyub (2014)	Robustness = B – C Rapidity = $\frac{A-B}{t_1-t_0}$	See Figure 1	Robustness units: percentage Rapidity units: average recovery rate in percentage per time Simple and straightforward metrics, easy for comparisons
Bruneau et al. (2003)	Loss of resilience R' $R'=\int_{t0}^{t1}[100-Q(t)]dt$	Q(t): the infrastructure quality, or performance of a system at a given time t. t_0 : the time of incident or disturbance occurrence. t_1: time when restoration is completed (quality of infrastructure is 100%). See symbols in Figure 1	R' corresponds to the area above the resilience curve measured from t_0 to t_1
Bruneau and Reinhorn (2007)	Resilience R $R=\int_{t0}^{t1}Q(t)dt$	Same as above	R corresponds to the area below the resilience curve measured from t_0 to t_1
Attoh-Okine et al. (2007)	$R=\frac{\int_{t0}^{t1}Q(t)dt}{100(t_1-t_0)}$	Same as above	Units: performance per unit time, where performance can be measured in percent (Figure 1).
Cimellaro et al. (2009)	$R=\frac{\int_{t0}^{th}Q(t)dt}{(t_h-t_0)}$	t_h: time horizon (for a portfolio of bridges this can be the maximum recovery time).	R is calculated for a larger period t_h (or time horizon), so that a faster recovery results to higher values of R.

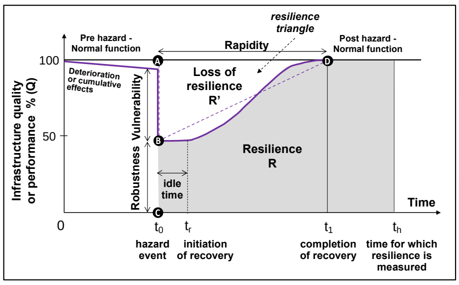
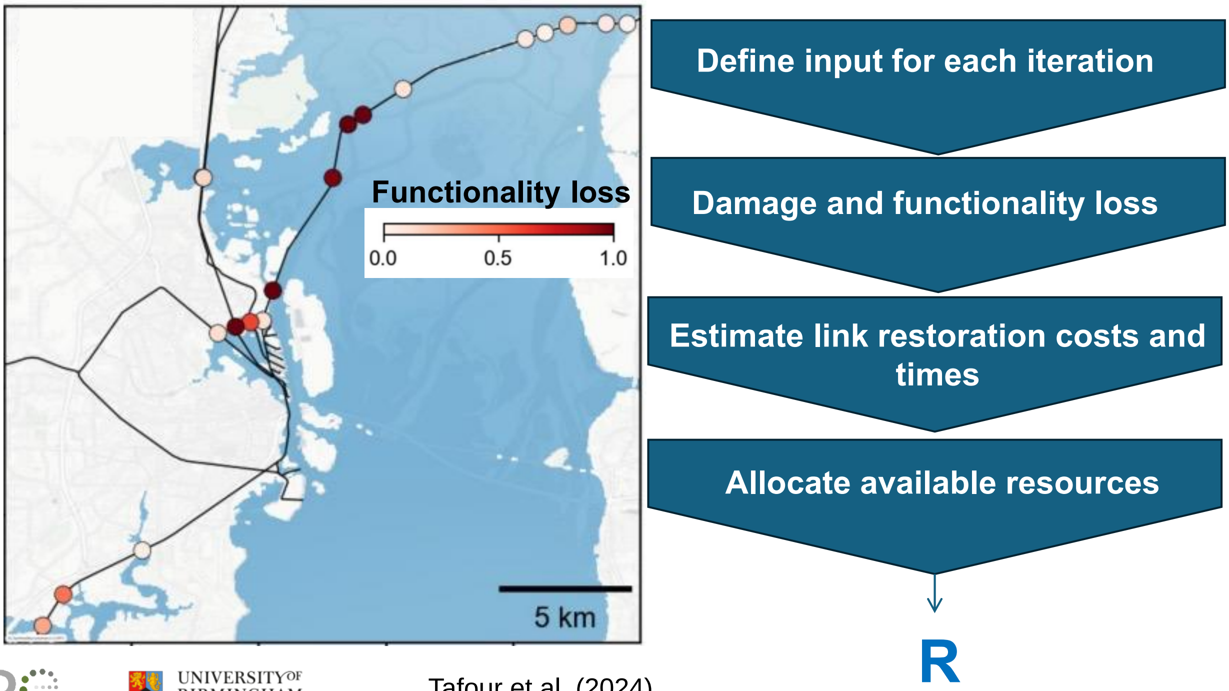


Figure 1: Resilience model

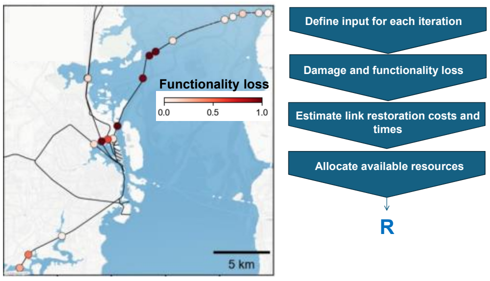
Source: Argyroudis, 2022

Resilience-based decision making



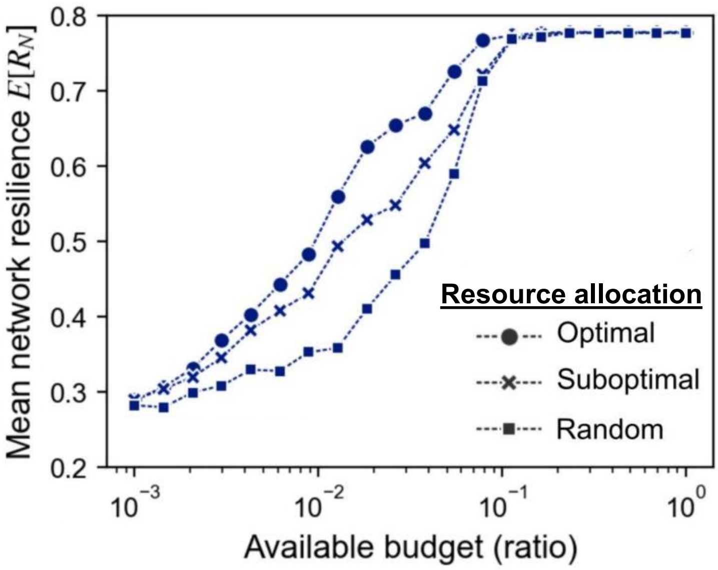
Tafour et al. (2024)

Resilience-based decision making



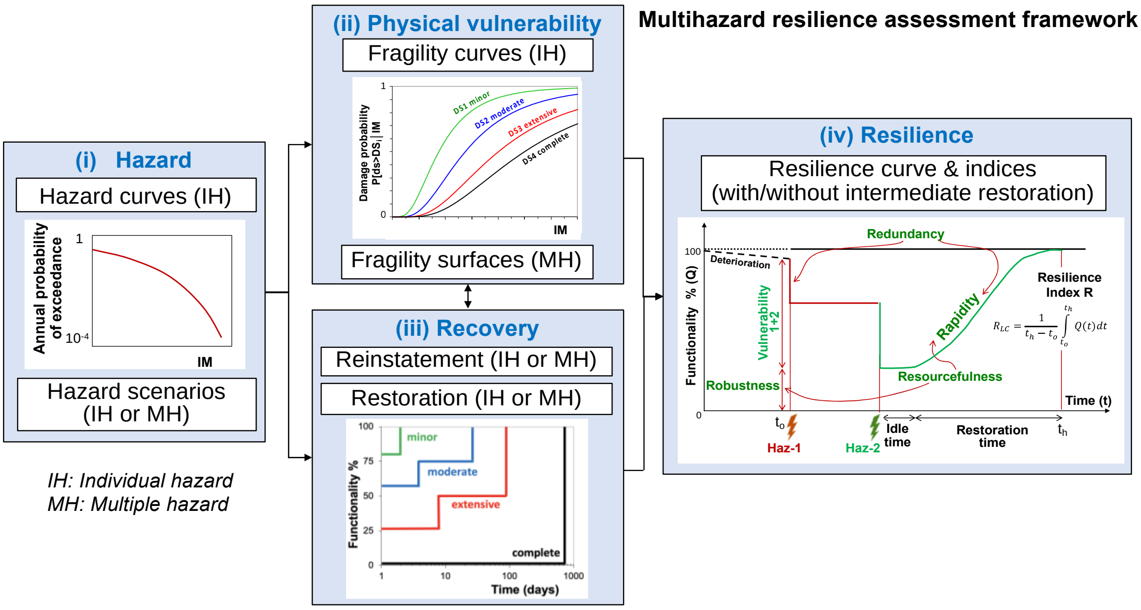
→**Allocating randomly results in significant lower R**

→**Diminishing returns on R as the budget increases**



Case studies

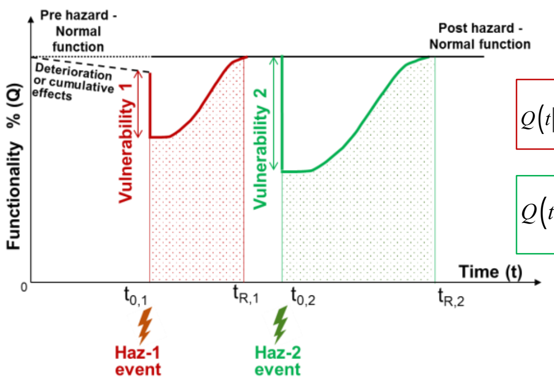
Multihazard resilience assessment framework



Argyroudis, Mitoulis et al. 2020

Case studies

Resilience assessment for multiple hazards: *restoration after Haz-1 and before Haz-2*



$$Q(t|IM_1) = \sum_{i=0}^{n_{DS_1}} Q_1[t|DS_{i,1}]P[DS_{i,1}|IM_1] \qquad t_{0,1} < t < \min(t_{R,1}, t_{0,2})$$

Equation (2)

$$Q(t|IM_2) = \sum_{i=0}^{n_{DS_2}} Q_2[t|DS_{i,2}]P[DS_{i,2}|IM_2] \qquad t_{0,2} < t < t_{R,2}$$

Equation (3)

Vulnerability 1: fragility functions for the initial or deteriorated asset

Vulnerability 2: fragility functions for the retrofitted asset

$$(\;\geq\; | \;=\;) = \Phi\left(\frac{(-)}{}\right)$$ *Equation (1)*

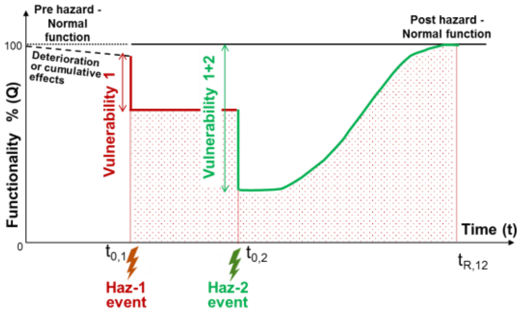
Resilience Index

$$R = \frac{1}{t_{R,2} - t_{0,1}} \int_{t_{0,1}}^{t_{R,2}} Q(t)dt$$

Argyroudis, Mitoulis et al. 2020

Case studies

Resilience assessment for multiple hazards:
without restoration after Haz-1 and before Haz-2 occurs



$$Q(t\,|\,IM_2) = \sum_{i=0}^{n_{DS_1}} \sum_{j=0}^{n_{DS_2}} Q_{12}\left[t\middle|DS_{i,1}, DS_{j,2}\right] P\left[DS_{j,2}\middle|DS_{i,1}, IM_2\right] \qquad t_{0,2} < t < t_{R,12}$$

Equation (4)

Vulnerability 1: fragility functions for the initial or deteriorated asset

Vulnerability 1+2: fragility functions for the damaged asset *(state-dependent fragility functions are needed)*

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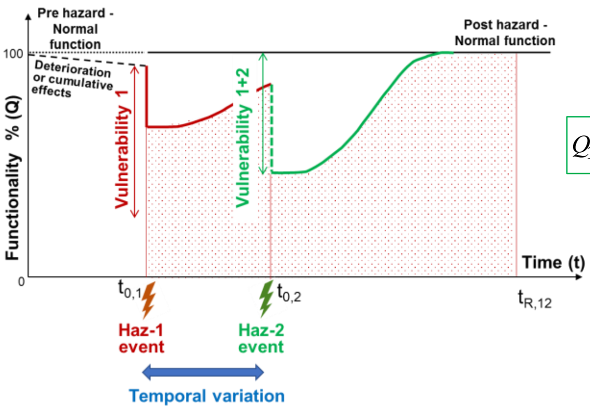
Argyroudis, Mitoulis et al. 2020

Case studies

Resilience assessment for multiple hazards:
Haz-2 occurs before the restoration due to Haz-1 is completed



$$Q_{12}\left[t\middle|DS_{i,1}, DS_{j,2}\right] = Q_1\left(t\middle|IM_1\right) - \left\{1 - Q_2\left[t - t_{02}\middle|DS_{i,1}, DS_{j,2}, t_{02}\right]\right\}$$

Equation (6)

Resilience Index

$$= \frac{1}{_{,12} - _{0,1}} \int_{0,1}^{,12} (\ )$$

Vulnerability 1: fragility functions for the initial or deteriorated asset

Vulnerability 1+2: fragility functions for the damaged/partially restored asset

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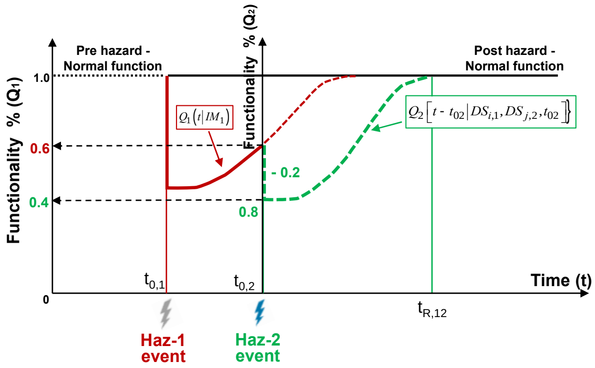
Case studies

Resilience assessment for multiple hazards:

Haz-2 occurs before the restoration due to Haz-1 is completed



Note:
The loss of functionality *Q1* (capacity) due to Haz-1 does not cause the same loss of functionality (capacity) for the effects of Haz-2, *Q2 (due to different intensity and bridge condition)*

$$Q_{12}\left[t \middle| DS_{i,1}, DS_{j,2}\right] = Q_1\left(t \middle| IM_1\right) - \left\{1 - Q_2\left[t - t_{02} \middle| DS_{i,1}, DS_{j,2}, t_{02}\right]\right\}$$

$$= 0.6 - (1 - 0.8) = 0.4$$

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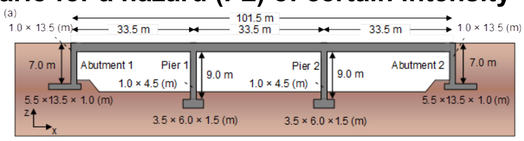
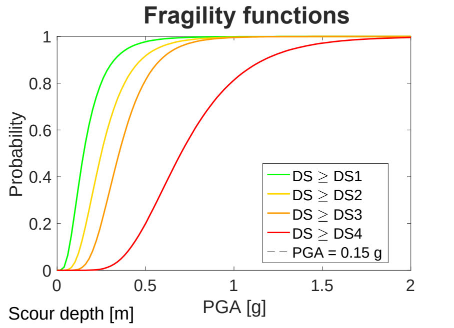
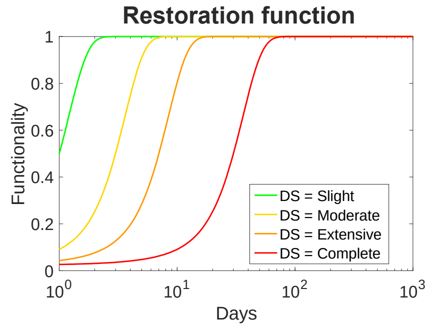
Case studies

Example 1:

Restoration of functionality after a scenario for a hazard (FL) of certain intensity







Fragility curves		
Damage State	**Median (m)**	**Sigma**
Slight	0.15	0.6
Moderate	0.25	0.5
Extensive	0.35	0.4
Collapse	0.7	0.4

Restoration curves		
Damage State	**Mean (days)**	**Sigma (days)**
Slight	1	0.5
Moderate	3	1.5
Extensive	7	3.5
Collapse	30	15

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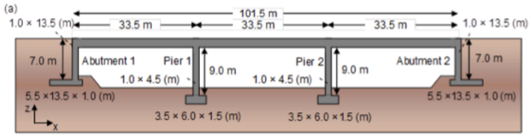
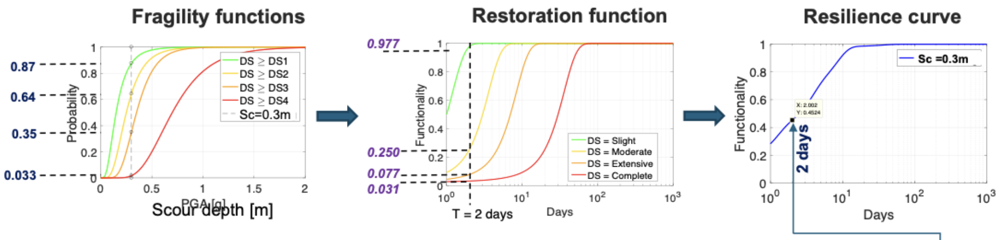
Case studies

Example 1:
Restoration of functionality after a scenario for a hazard (FL) of certain intensity (Sc=0.3m)

$$F[T = t] = \sum_{t=0}^{n_{DS}} F[DS_i, T = t] * P[DS_i]$$

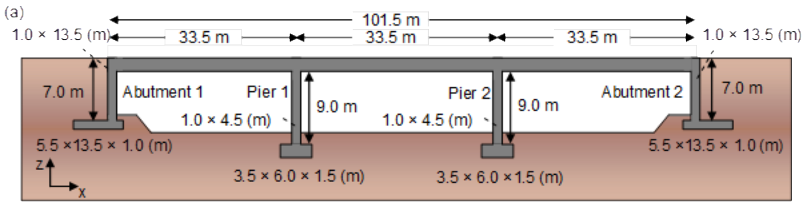




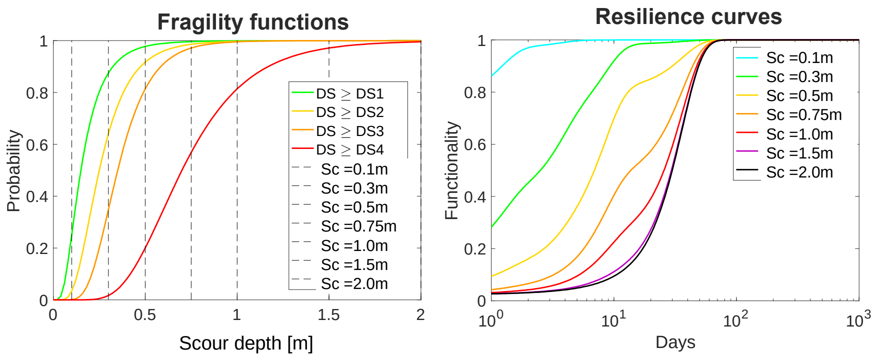
F(t=2days)= **0.13**x*1*+ **0.23**x*0.977*+**0.29**x*0.250*+**0.317**x*0.077*+**0.033**x*0.031* = **0.452**

1-0.87 **0.87-0.64**

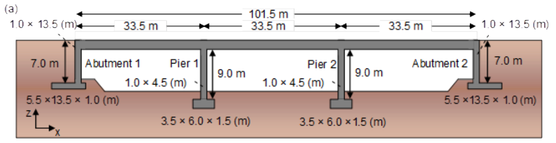
Example 2:
Restoration of functionality after 7 different scenarios (and hazard intensities)



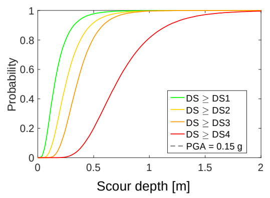
Deriving resilience curves for different Scour depths



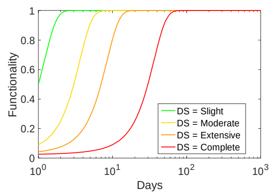
Example 3:
Improving resilience of a bridge with different restoration strategies



Fragility functions



Restoration functions

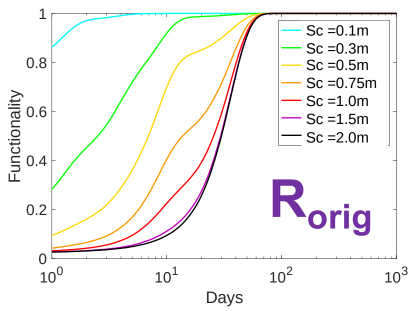


Fragility curves		
Damage State	Median (m)	Sigma
Slight	0.15	0.6
Moderate	0.25	0.5
Extensive	0.35	0.4
Collapse	0.7	0.4

Restoration functions		
Damage State	Mean (days)	Sigma (days)
Slight	1	0.5
Moderate	3	1.5
Extensive	7	3.5
Collapse	30	15

Original restoration strategy

Resilience curves



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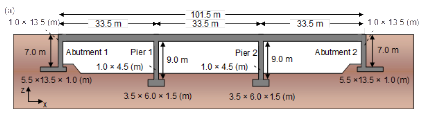
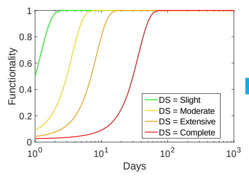
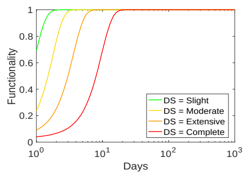
Case studies
Example 3:
Improving resilience of a bridge with different restoration strategies



Original Restoration functions



Improved Restoration functions

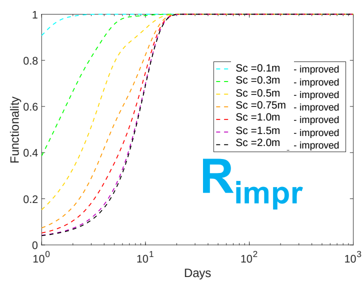


Restoration functions - Original restoration strategy		
Damage State	Mean (days)	Sigma (days)
Slight	1	0.5
Moderate	3	1.5
Extensive	7	3.5
Collapse	30	15

Restoration functions – Improved restoration strategy		
Damage State	Mean (days)	Sigma (days)
Slight	0.8	0.4
Moderate	1.5	0.7
Extensive	3	1.5
Collapse	8	4

Improved restoration strategy

Resilience curves



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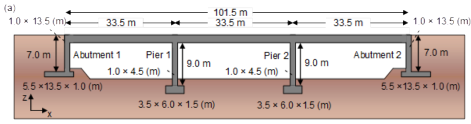
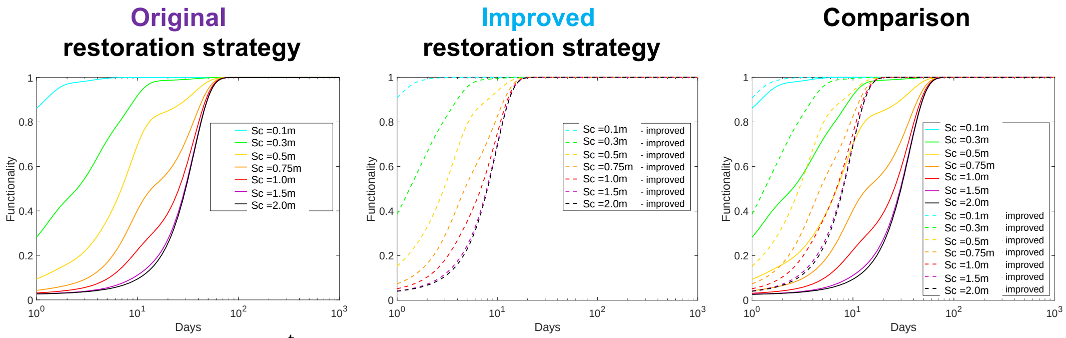
Case studies

Example 3:
Improving resilience of a bridge with different restoration strategies



Resilience curves



$$R = \frac{1}{t_h - t_o} \int_{t_o}^{t_h} Q(t)$$

$R_{orig} < R_{impr}$

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Case study

Resilience quantification:

- Step by step quantification of resilience for critical infrastructure considering different hazard and adaptation scenarios

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