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

This project has received funding from the Horizon Europe Programme under the Marie Skłodowska-Curie Staff Exchanges Action (GA no. 101086413). Co-funded by the UK Research & Innovation, and the Swiss State Secretariat for Education, Research & Innovation.

European Commission

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Contributors to the Massive Open Online Course:

Resilience, Sustainability & Digitalisation in Critical Infrastructure

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Lecture 1

Massive Open Online Course

Resilience, Sustainability & Digitalisation in Critical Infrastructure

Introduction to Resilience, Sustainability and Digitalisation of critical infrastructure systems

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Lecture 1 Outcomes

- Define resilience and its properties for critical infrastructure assets, networks and systems.
- Define sustainability and its properties for critical infrastructures assets, networks and systems.
- Explain the importance of digitalisation and its applicability for enhancing resilience and sustainability of critical infrastructure assets, networks and systems.

ACTIVITY 1: What is Resilience?

- The history of resilience: from economy to engineering
- Resilience in critical civil infrastructure
- The many faces of resilience. What is your experience?

The history of resilience: from economy to engineering

OED | Oxford English Dictionary

The word resilience first appears in books in 1626.

I.1. † The action or an act of rebounding or springing back; rebound, recoil. Obsolete. **1626–1866**

1626 Whether there be any such Resilience in Eccho's.
F. Bacon, *Sylva Sylvarum* §245

1656 *Resilience*, a leaping or skipping back, a rebounding.
T. Blount, *Glossographia*

1834 Mightier far was the joy of thy sudden resilience.
S. T. Coleridge, *Hymn to Earth* in *Friendship's Offering* 166

1843 The Heaviest..has its deflexions..nay at times its resiliences, its reboundings.
T. Carlyle, *Past & Present* i. ii. 15

1866 The heart does not always propel without resilience.
J. Martineau, *Essays Philosophical & Theological* 1st Series 41

I.2.a. Elasticity; the power of resuming an original shape or position after compression, bending, etc. **1807–**

1807 The resilience is jointly proportional to its strength and its toughness, and is measured by the product of the mass and the square of the velocity of a body capable of breaking it.
T. Young, *Course of Lectures on Natural Philosophy* vol. I. xiii. 143

1822 The natural elasticity or resilience of the lungs.
J. M. Good, *Study of Medicine* vol. II. 10

1824 The term modulus of resilience, I have ventured to apply to the number which represents the power of a material to resist an impulsive force.
T. Tredgold, *Practical Essay on Strength of Cast Iron* 82

1867 To bend back again.., if the metal possesses sufficient resilience to do so.
C. T. F. Young, *Fouling Iron Ships* 164

1897 [The skin] giving a sensation of the loss of all elasticity or resilience.
T. C. Allbutt et al., *System of Medicine* vol. IV. 470

1937 This Goodrich putty, made of rubber, never loses its resilience.
Life 13 September 18/2 (advertisement)

1990 Linen as a fabric is valued for its resilience and strength.
Connoisseur September 70/1

The history of resilience: from economy to engineering

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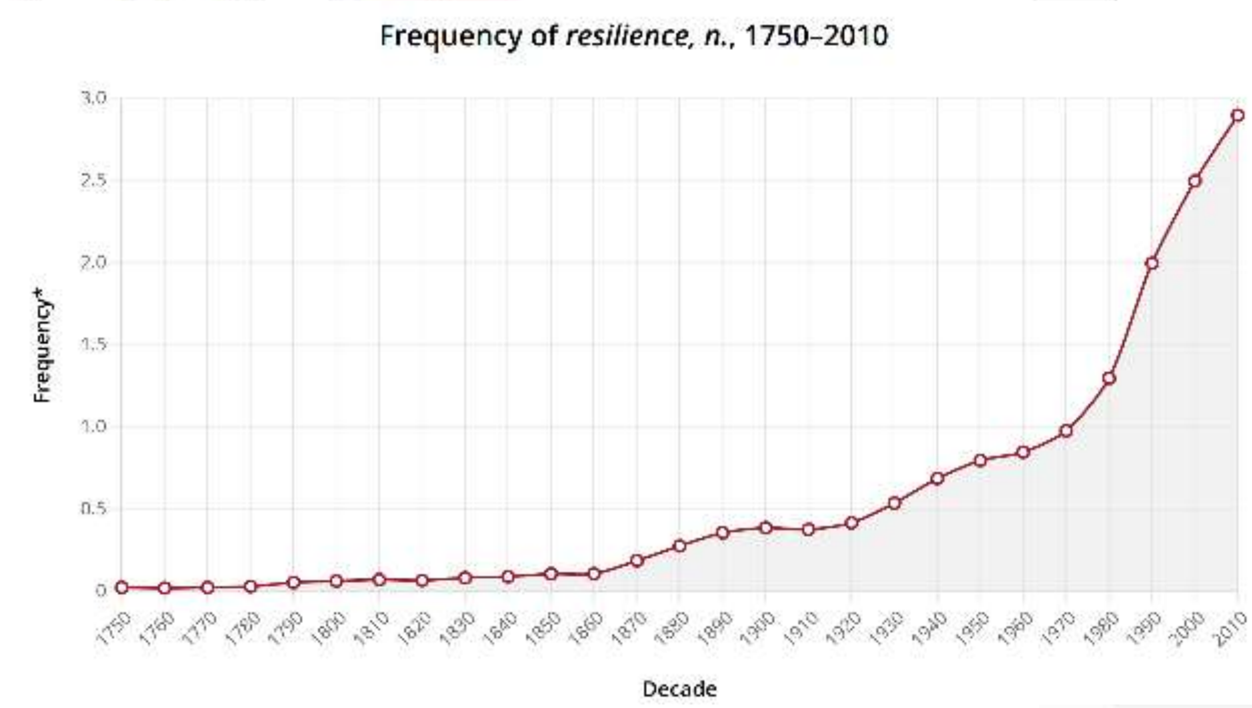

* Occurrences per million words in written English

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The history of resilience: definitions

Reference	Definition
Holling (1973)	Ecological systems resilience is a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables
Horne and Orr (1998)	Resilience is the ability of a system to withstand stresses of environmental loading...[it is] a fundamental quality found in individuals, groups, organizations, and systems as a whole
Gunderson et al. (2002)	Engineering resilience is the speed of return to the steady state following a perturbation ecological resilience is measured by the magnitude of disturbance that can be absorbed before the system is restructured
Bruneau et al. (2003)	Resilience is defined in terms of three stages: the ability of a system to reduce the probability of an adverse event, to absorb the shock if the adverse event occurs, and to quickly re-establish normal operating conditions. So resilience thus encompasses the four characteristics of robustness, redundancy, resourcefulness, and rapidity. Are considered four types of resilience: technical; organizational; economic; and social
Resilience Alliance (2005)	Ecosystem resilience is the capacity of an ecosystem to tolerate disturbance without collapsing into a qualitatively different state that is controlled by a different set of processes. Thus, a resilient ecosystem can withstand shocks and rebuild itself when necessary.
United Nations Office for Disaster Risk Reduction (UNISDR, 2009)	The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions
National Academy of Sciences (NAS, 2012)	The ability of a system to perform four functions with respect to adverse events: (1) planning and preparation, (2) absorption, (3) recovery, and (4) adaptation.

The history of resilience: from economy to engineering

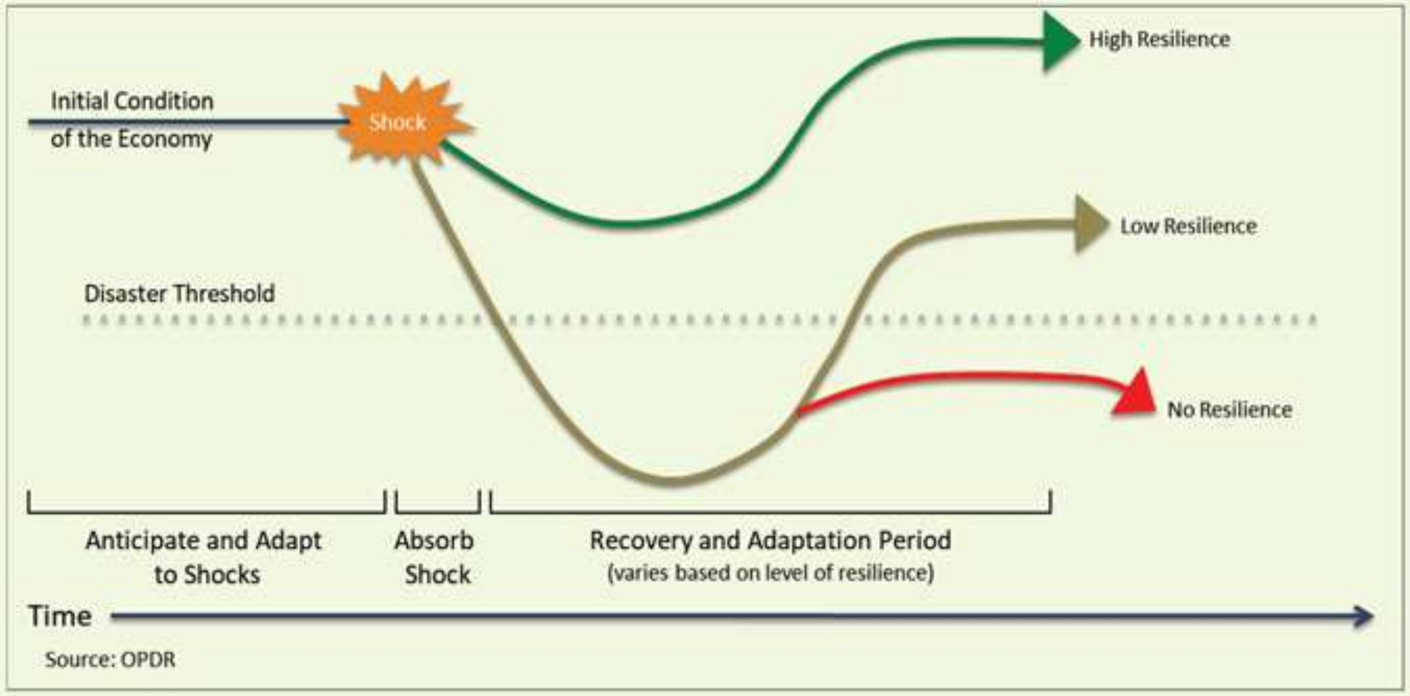
Resilience concepts and strategies used extensively in the banking and finance system post-1970 record of severe recessions and financial crises.

Resilience in economy includes two key components *(Hallegatte 2014).*

1. the ability of an **economy as a whole** to cope, recover from and reconstruct after a shock;
2. the resilience of **individual households or firms**, and their ability to cope with or recover from a shock and adapt to changing economic circumstances in the wider economy. In this case, it can relate to the distributional effects of a shock (who is affected and how) as well as the vulnerability of individuals to the shock and the nature of any welfare provisions that are in place.

Resilience in the economy focuses on minimising overall **welfare losses**. Greater resilience reduces the economic losses from shocks over time.

Alternatively, resilience can be viewed as a means to promote **welfare gains**. This perspective, central to development economics, suggests that strengthening the economic assets of individuals and communities enhances their ability to withstand economic shocks.



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

resilience

Rapidity
the ability to meet priorities and goals in time to prevent losses and future disruptions.

Robustness
the ability of systems to withstand a certain level of stress without suffering loss of function.

Resourcefulness
the ability to identify problems and resources when threats may disrupt the system.

Redundancy
the ability to have various paths in a system by which forces can be transferred to enable continued function

The dimensions of resilience

POPULATION AND DEMOGRAPHICS
Composition, Distribution, Socio-Economic status, etc.

ENVIRONMENTAL/ECOSYSTEM
Air quality, Soil, Biomass, Biodiversity, etc.

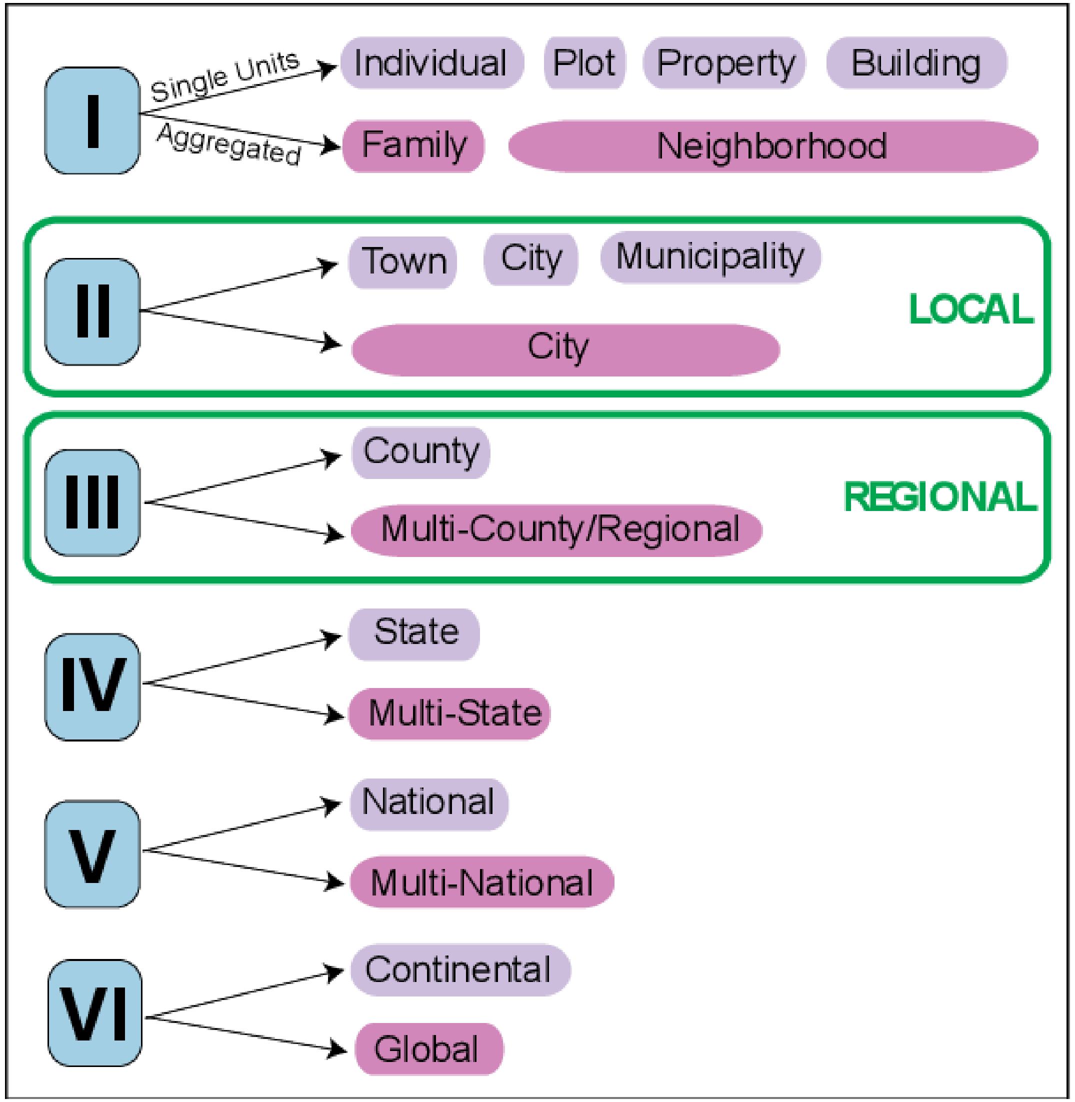
ORGANIZED GOVERNMENTAL SERVICES
Legal and security services, Health services, etc.

PHYSICAL INFRASTRUCTURE
Facilities, Lifelines, etc.

LIFESTYLE AND COMMUNITY COMPETENCE
Quality of Life, etc.

ECONOMIC DEVELOPMENT
Financial, Production, Employment distribution, etc.

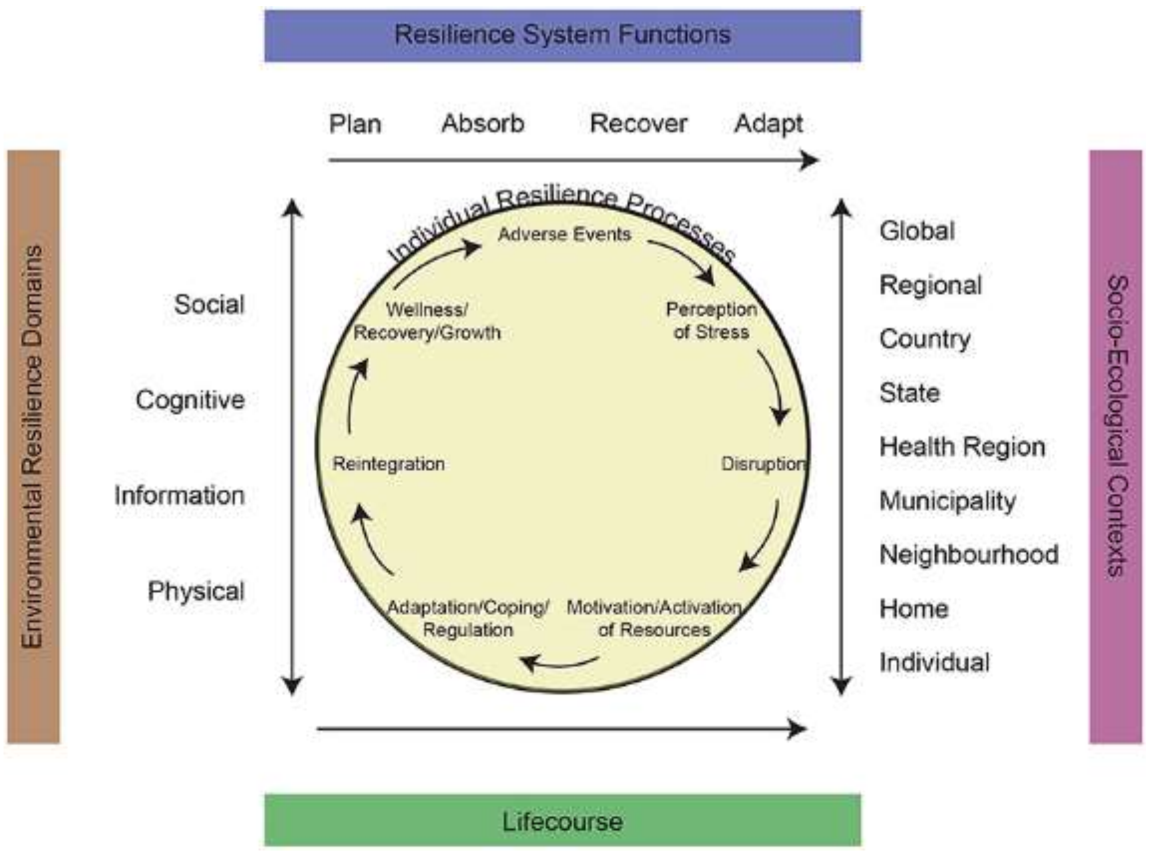
SOCIAL-CULTURAL CAPITAL
Education services, Child and elderly care services, etc.



The PEOPLES Resilience Framework and associated Geographic Scales (Renschler et al. 2010)

The domains of resilience

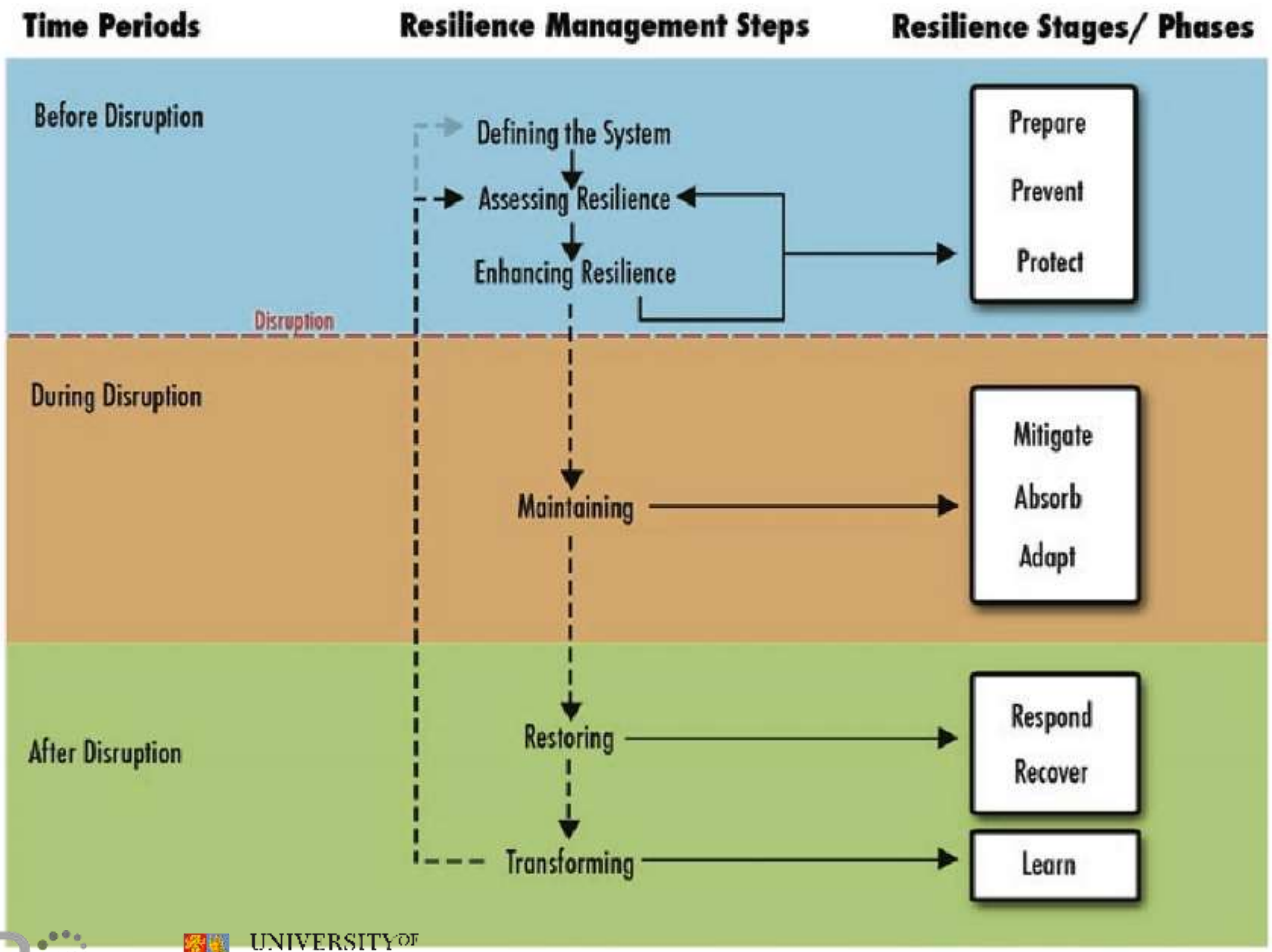
physical	infrastructures, facilities, equipment, sensors, system states, capabilities, functional levels, interconnection
information	creation, manipulation, storage of data, literacy, knowledge, access to information, resources that promote understanding of resilience pathways, solutions to adverse events
cognitive	understanding, frameworks and mental models, preconceptions, biases, and values, cope with stressors, baseline health and needs
social	positive social interaction, community participation, participatory decision making, self-synchronisation between individuals and entities



Resilience concepts

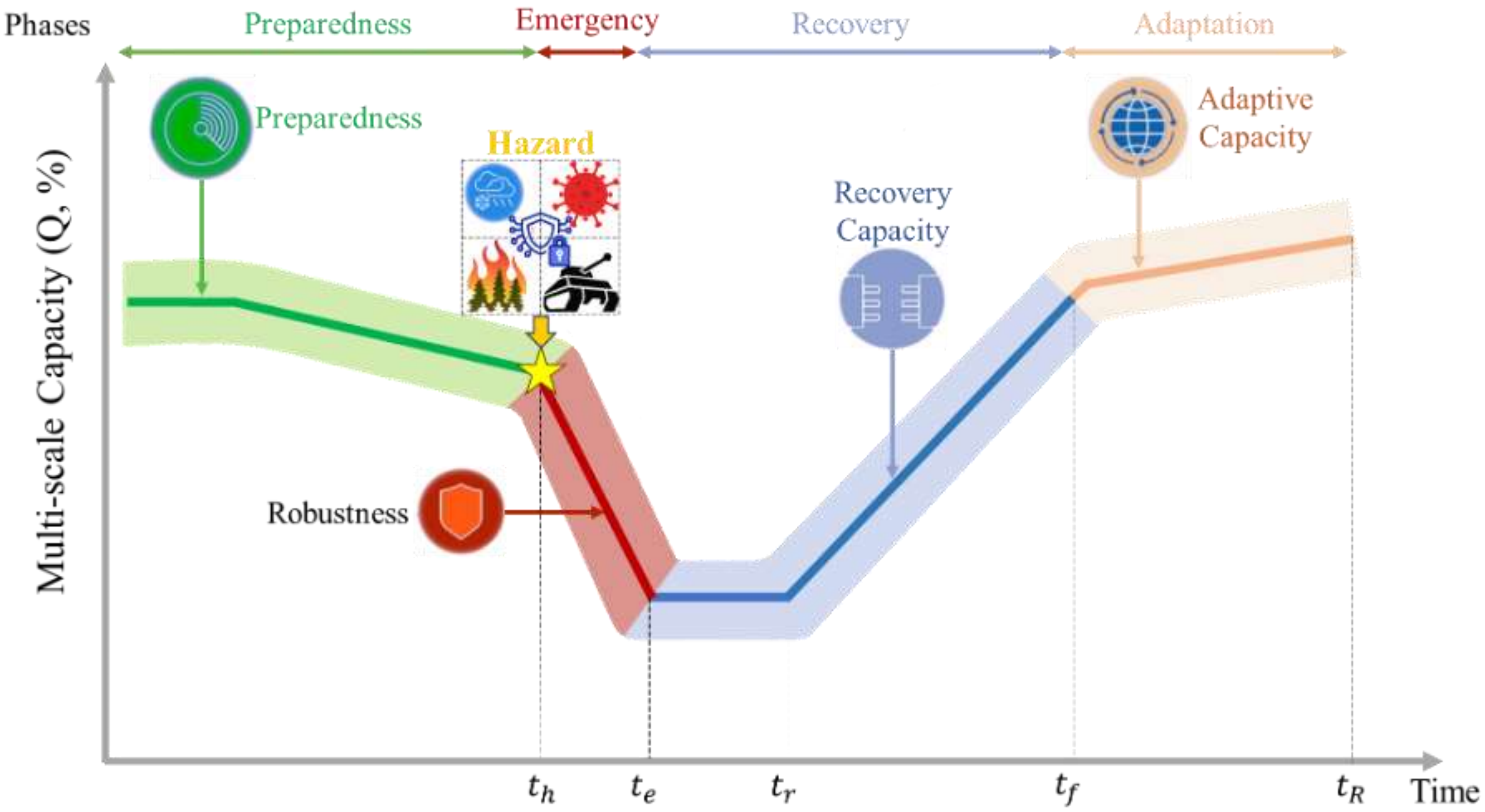
Qi and Mei (2024)

Role of resilience in systems, emphasising importance of combating disruptions



Linkov, I., & Trump, B. D. (2019). *The science and practice of resilience*. Cham: Springer International Publishing.

Resilience in critical civil infrastructure - the four phases



The four components and phases of resilience

t_h: time point of hazard occurrence; t_e: end of hazard occurrence;

t_r: start of recovery; t_f: recovery of full functionality

Reflection:

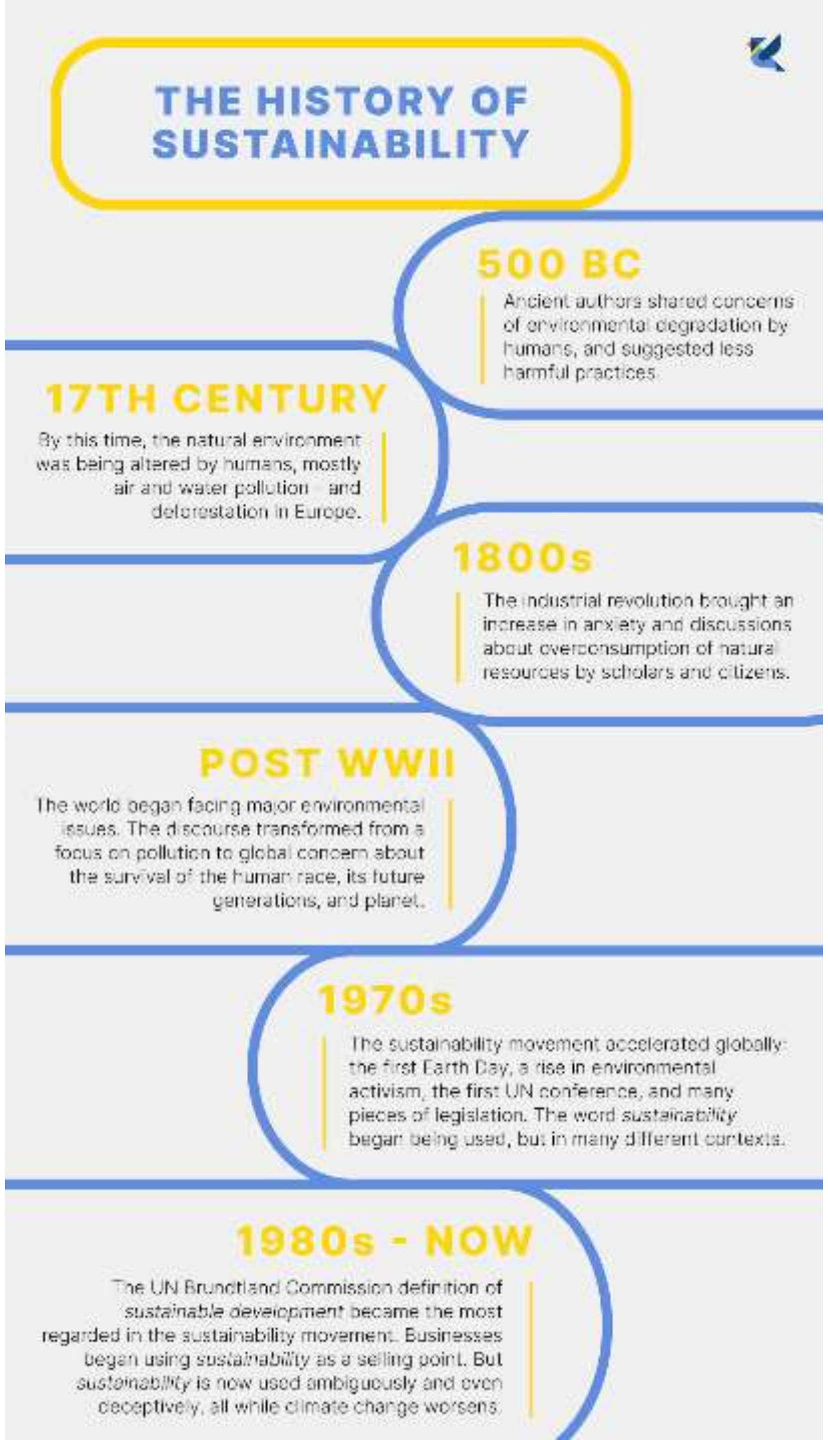
Think about an occasion of your professional life where you incorporated resilience and its many faces of resilience.

What is your experience?

ACTIVITY 2: What is Sustainability?

- A brief history of sustainability
- Sustainable Development Goals and policies
- Sustainability in critical civil infrastructure
- What is your experience of sustainability?

A brief history of sustainability



Source: [thesustainableagency]

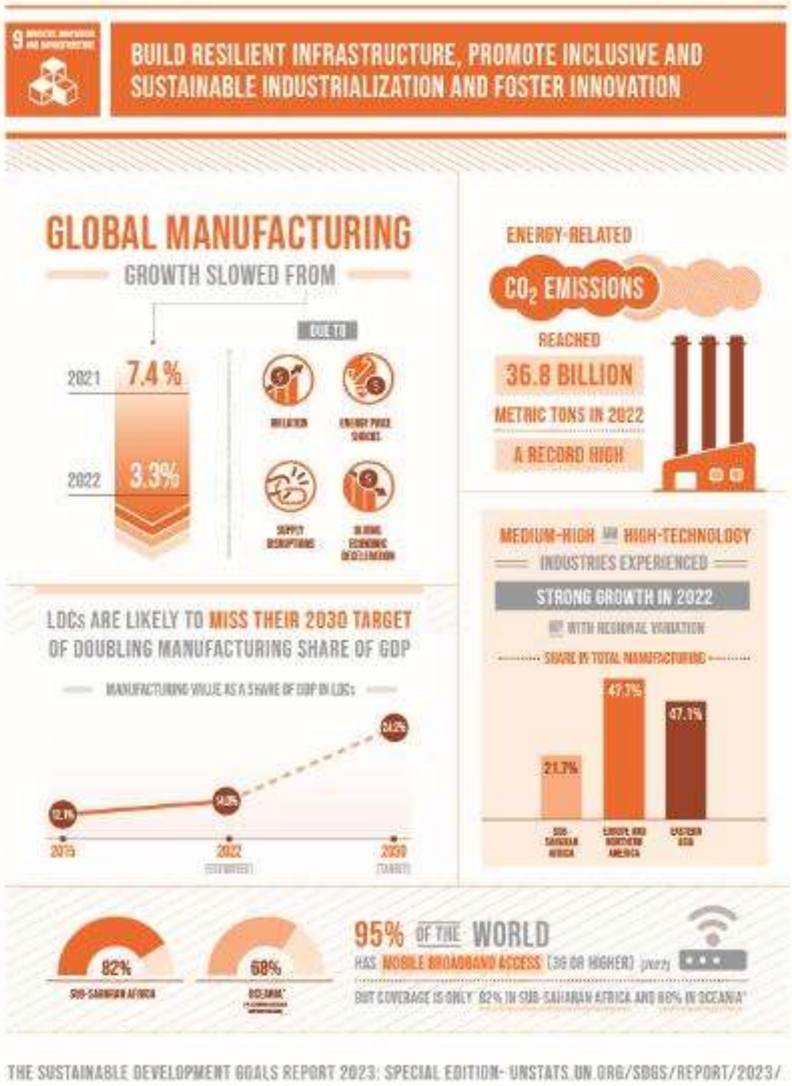
Sustainable Development Goals and policies

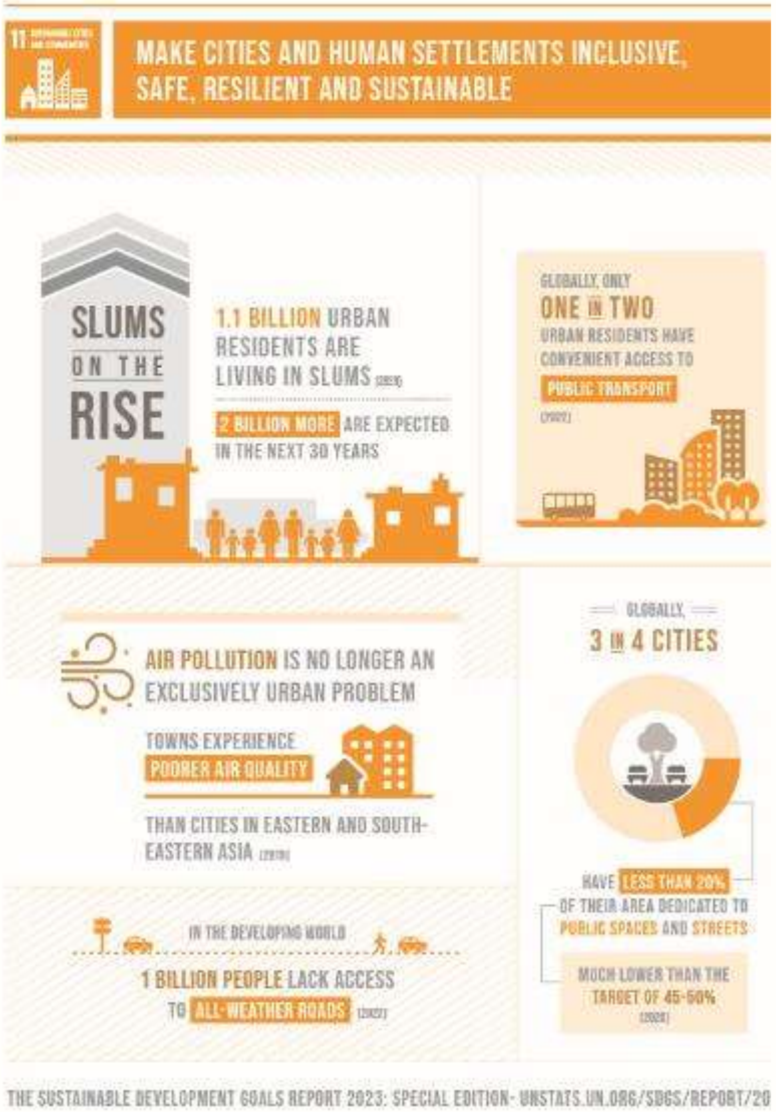
The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, provides a shared blueprint for peace and prosperity for people and the planet, now and into the future.

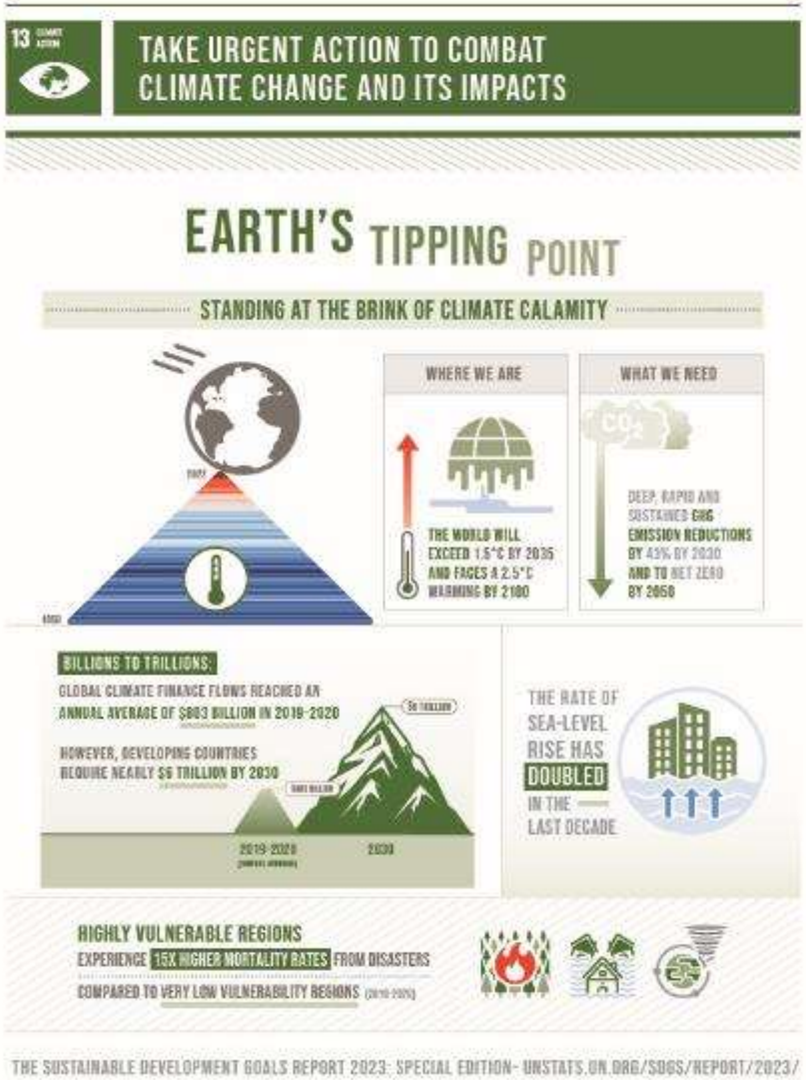
At its heart are the 17 Sustainable Development Goals (SDGs), which are an urgent call for action by all countries - developed and developing - in a global partnership. They recognise that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve our oceans and forests.

Source: sdgs.un.org

Sustainable Development Goals and policies







Source: sdgs.un.org

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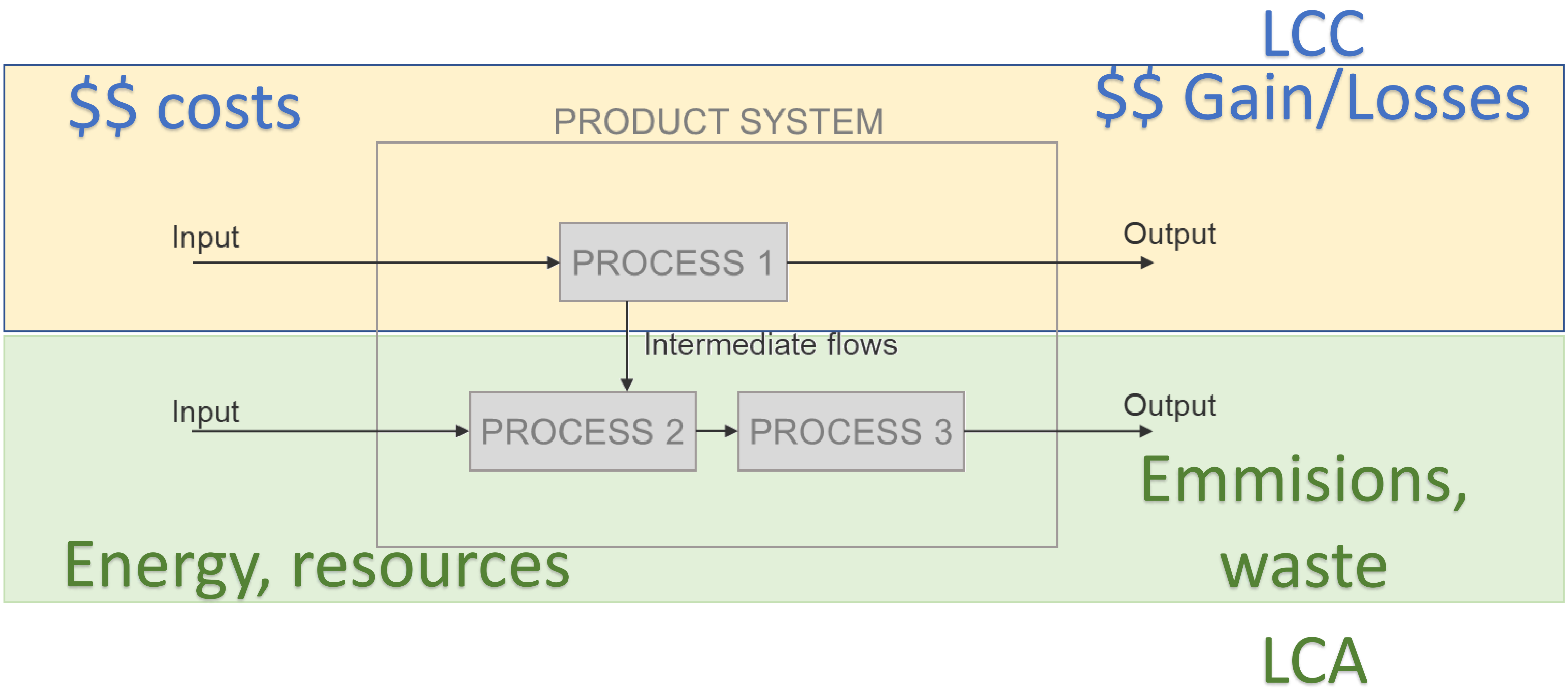
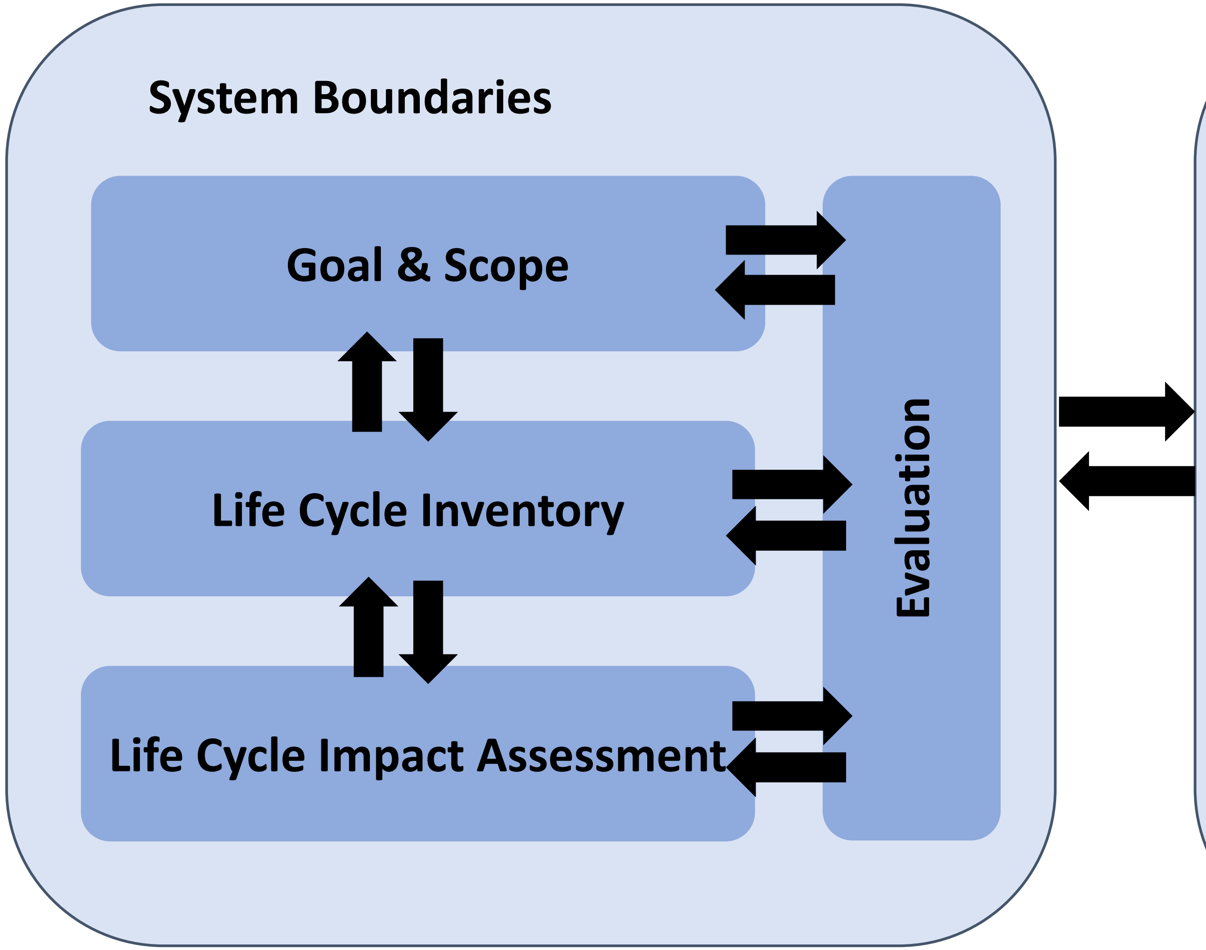
Life Cycle Analyses



Life Cycle Assessment – ISO 14040 - 14044

What:

"Compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system during a product's lifetime."

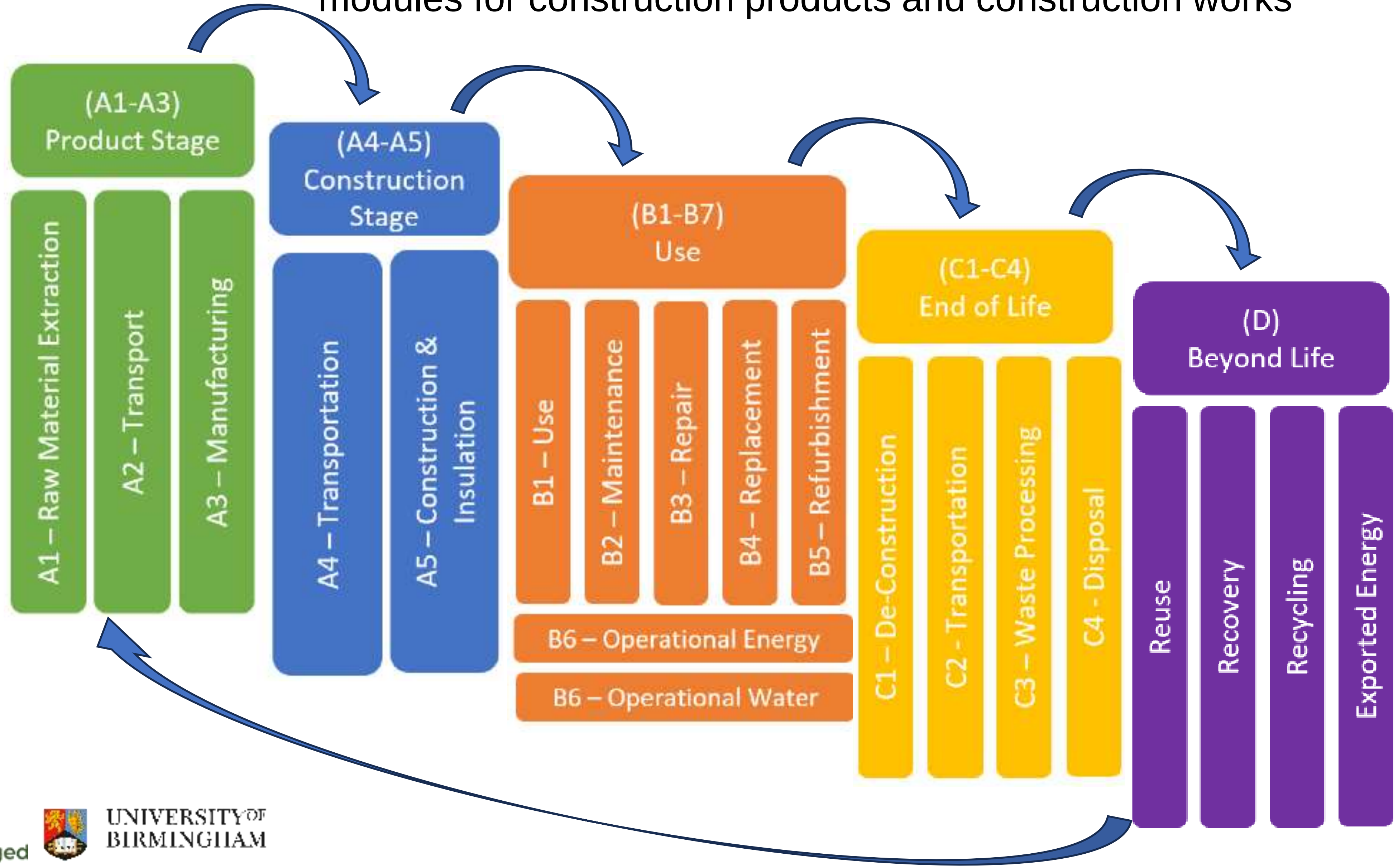


Purposes

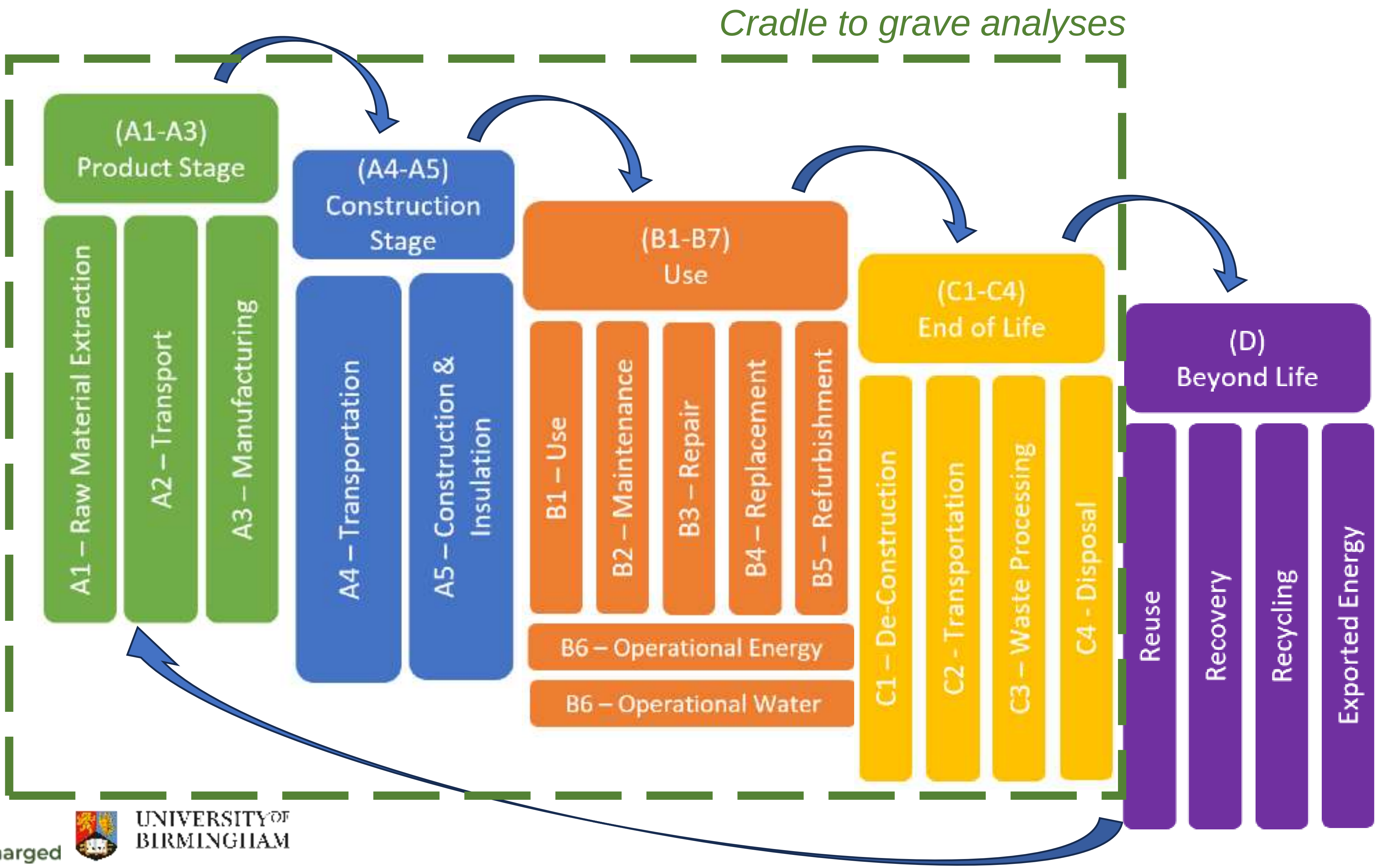
- Development and improvement of products
- Strategic planning
- Political decision-making processes
- Marketing
- Other

Sustainability in critical civil infrastructure

Common four life-cycle stages and their information modules for construction products and construction works



Sustainability in critical civil infrastructure



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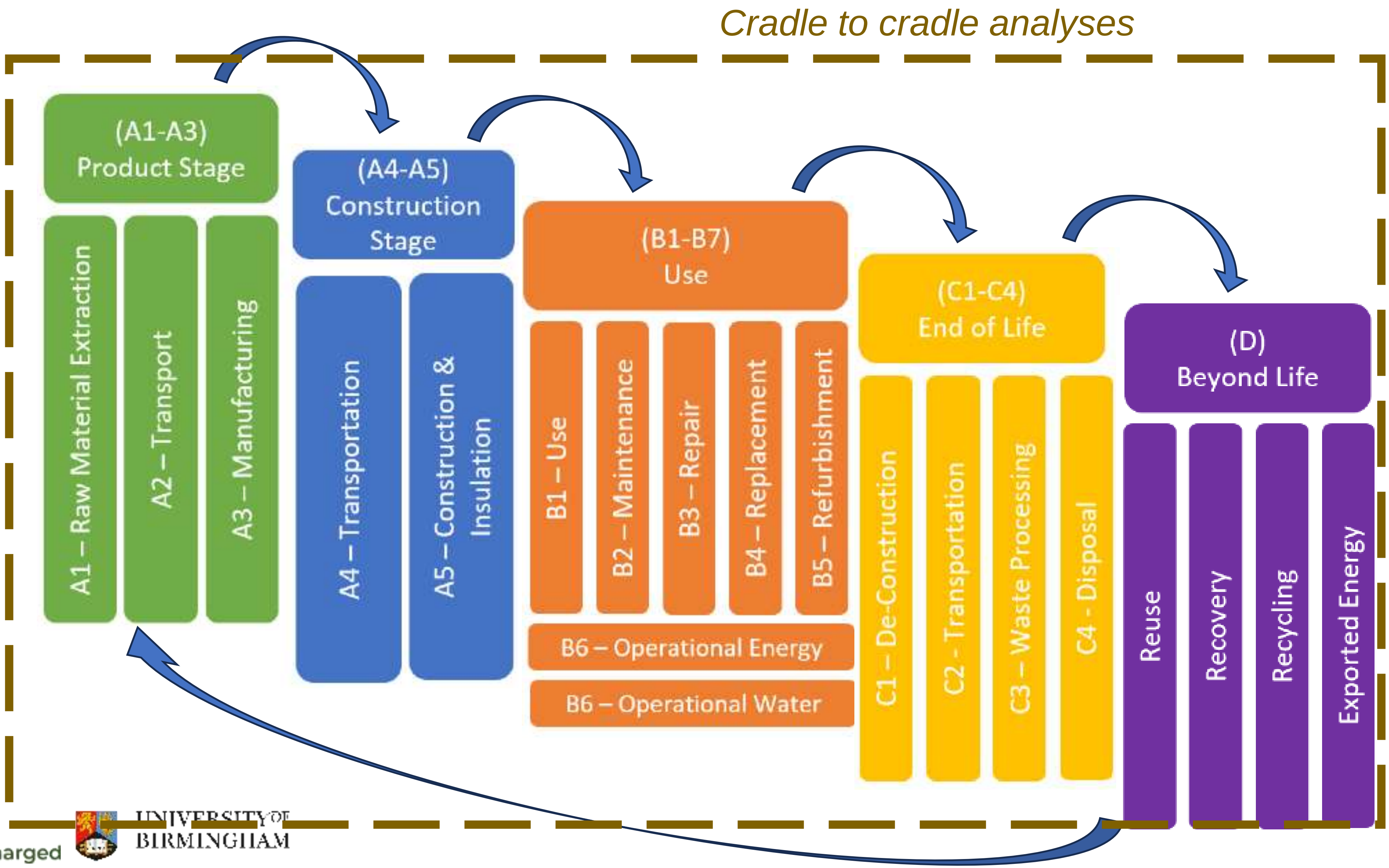
Sustainability in critical civil infrastructure



Sustainability and circularity – options for end-of-life of products

- **Recycling →** Giving waste a new outlook on life. Recycling restores an object to its original state.

Examples: paper is transformed to pulp, plastics are melted and shaped into new objects (different)

- **Reuse→** Repurposing items and products for extended use.

Example. Shopping Bag reuse. No material processing

- **Recovery →** repurposing and processing most of the waste that would otherwise be discarded.

Example: Thermal recovery: timber elements are subjected to combustion.

Thermal energy is recovered from the combustion

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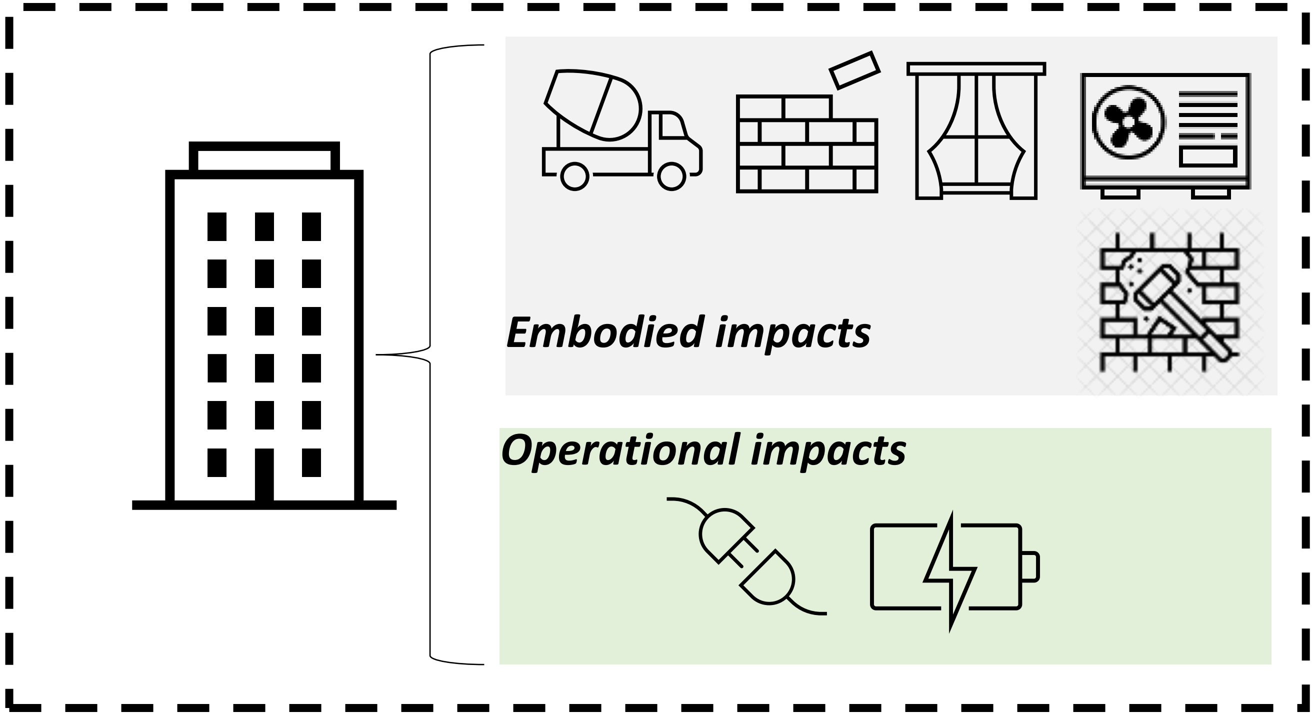
Sustainability in critical civil infrastructure – System boundaries
Example on a building and challenges



Building System Boundaries

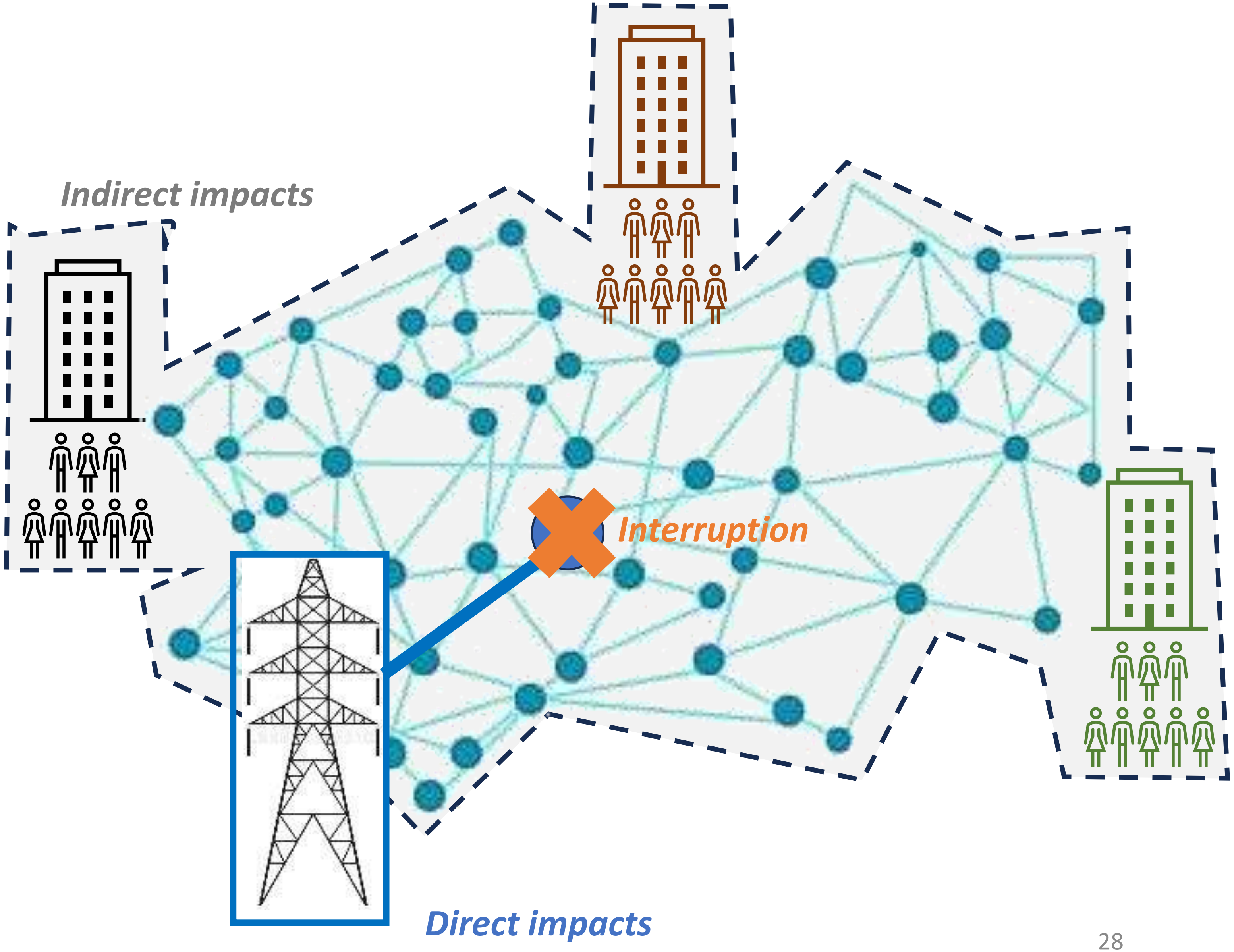
- High complexity
- Different components and materials
- Consideration of operational energy

- Time-Consuming data collection
- Need for data coming from different simulation tools
- Assessment of *direct* impacts (related to the each built systems)

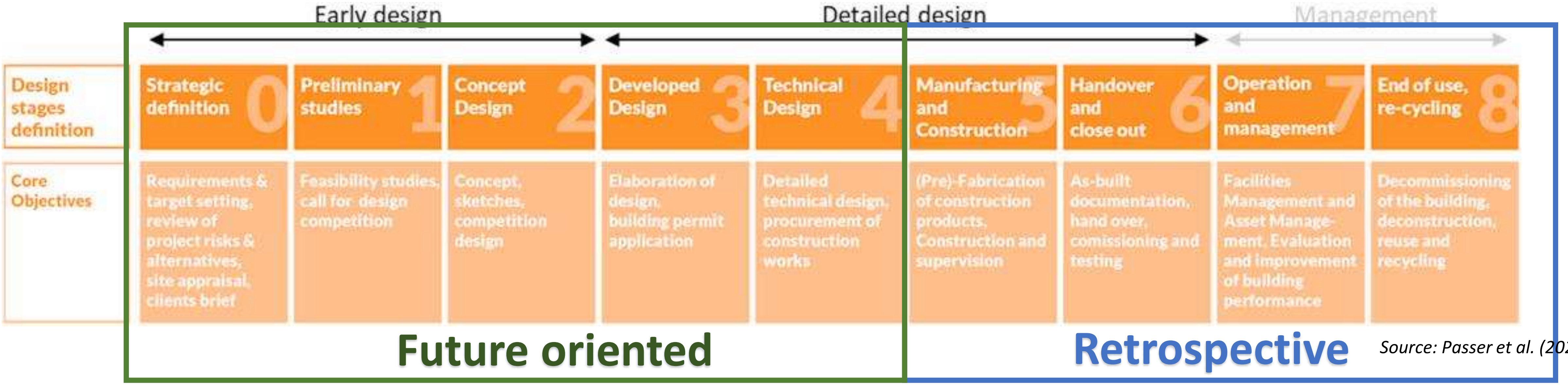
Sustainability in critical civil infrastructure – System boundaries
Example on infrastructure and challenges

- **Lower complexity of single infrastructure part (e.g. transmission tower)**
- **Communities are dependent from infrastructures**

- **Consideration of *indirect* impacts (*social, economic, environmental*) → increased complexity of data collections**



Sustainability Assessment and integration in planning process - challenges



Source: Passer et al. (2023)

Early decision making

- **LCA as a tool supporting the decision-making**
- **Improvement potential very high**
- **Uncertainties level high / very high**
- **Addressing uncertainties and communicating them essential task.**

Sustainnability Certification

BREEAM®

- **LCA as a final assessment tool**
- **All relevant decisions already occurred**
- **Improvement potential low**

Reflection:

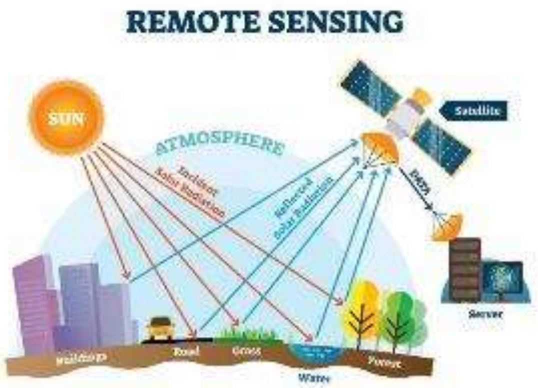
- Think about an occasion of your life where you considered sustainability.
- Give an example of a sustainable and non-sustainable infrastructure system.
- Mention sustainable solutions to critical infrastructure development, considering e.g. materials, resources, reuse.

ACTIVITY 3: What is digitalisation?

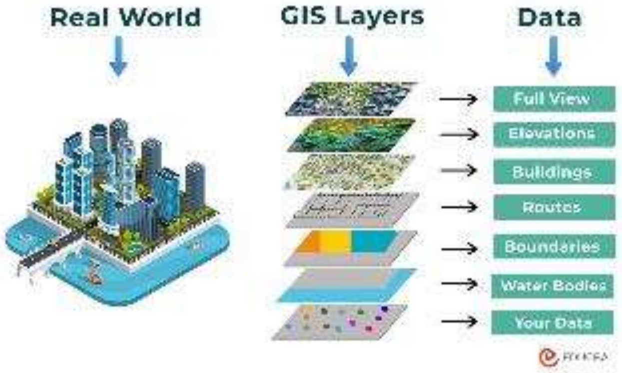
- Emerging technologies and digital data
- Digitalisation in critical infrastructure management
- Your experience in digitalisation

Type of technologies for monitoring & assessment

Remote Sensing provide high-resolution imagery and data about infrastructure assets. These technologies are useful for assessing large-scale projects.



Geographic Information Systems (GIS) combines spatial data with attribute information to create digital maps and models of infrastructure assets. It enables the visualisation, analysis, and management of infrastructure data.



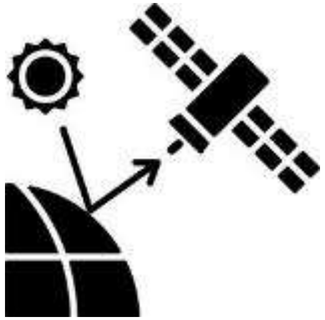
Non-Destructive Testing (NDT) techniques employ digital technologies to assess the condition of infrastructure components without causing damage.

Structural Health Monitoring (SHM) systems use sensors and digital technologies to continuously monitor the behaviour and health of structures.

Internet of Things (IoT) refers to a system of interconnected devices that have sensors and embedded processing abilities.

Mobile Applications could be designed for infrastructure assessment streamline data collection, documentation, and reporting processes.

Remote Sensing

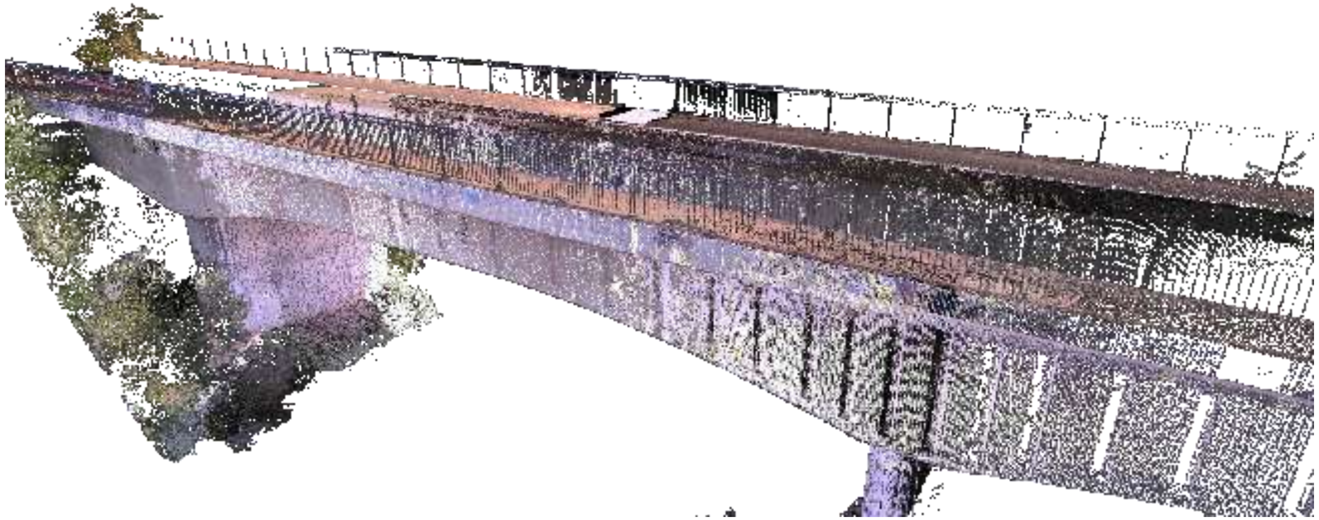


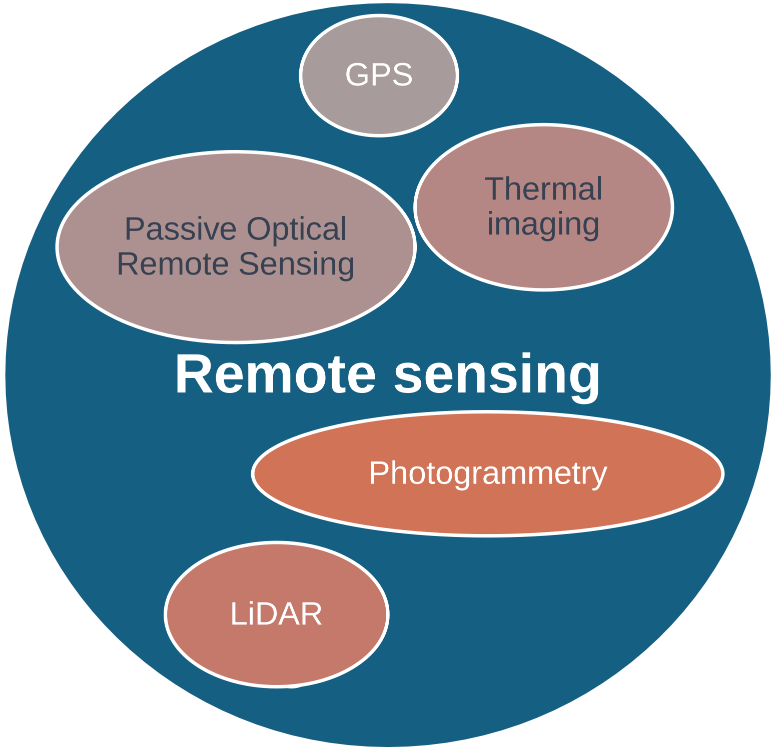
satellite

LiDAR

photogrammetry

total station





Remote sensing is the acquisition of information about an object without making physical contact, in contrast to in situ or on-site observation. It allows to capture, visualise, and analyse objects.

Structural Health Monitoring (SHM)

- Structural Health Monitoring (SHM) is a systematic process that involves using sensors, data acquisition systems, and analysis techniques to continuously monitor the condition and performance of infrastructure assets.
- The primary objective of SHM is to detect any changes or anomalies in the structure behaviour and health, providing early warnings of potential issues and aiding in maintenance and decision-making.
- SHM of infrastructure involves the following tasks:
  - Sensor deployment and data acquisition
  - Data analysis and interpretation
  - Condition assessment and remaining life estimation
  - Predictive maintenance
  - Long-term performance evaluation

Digital inspection of structures

Automated inspection framework consists of two main steps:

1. Utilising optical sensing theologies for remote automated data acquisition;
2. Data processing and inspection using AI techniques
3. Created digital models to continuously store, manage and analyze collected data

Markogiannaki et al. (2022)

Digital inspection of structures

Figure 1. Transport and Energy Assets and interdependencies

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Figure 2. Digital Technologies

Figure 3. UAV-mapping (drone aerial survey)

Figure 4. The digital twin of the bridge

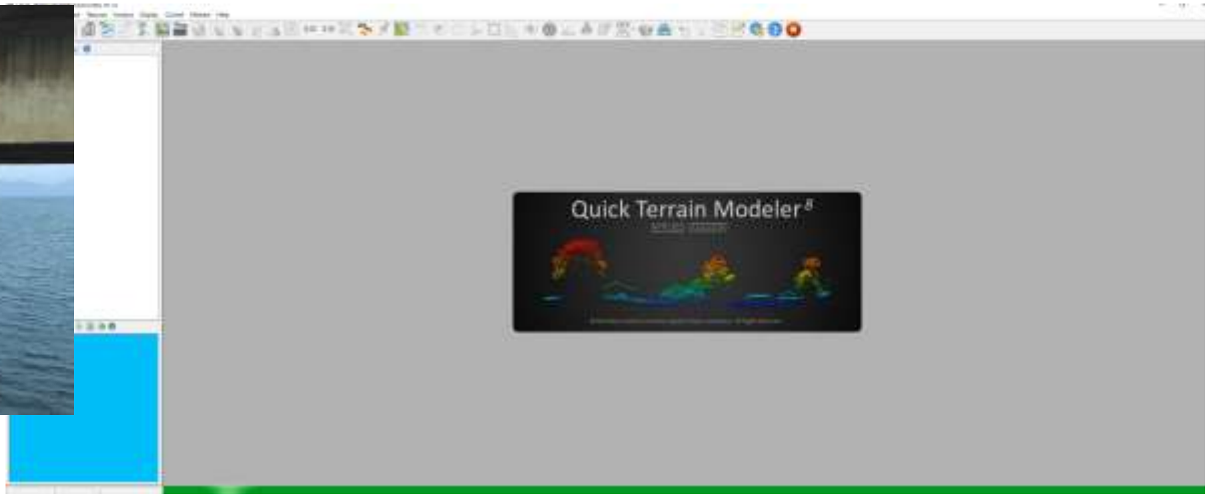


Figure 5. Laser scanner

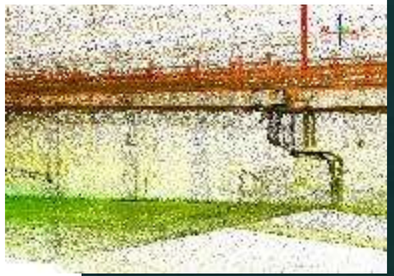


Figure 6. SAR interferometry (satellite imagery)

Digital inspection of structures

UAVs for enhancing post-disaster resilience of damaged structures

Loli M, Mitoulis SA et al. (2022)
Loli M, Mitoulis SA et al. (2022)

Machine learning

"field of study that gives computers the ability to learn without being explicitly programmed"

(Samuel, 1959)

"a computer program is said to learn from

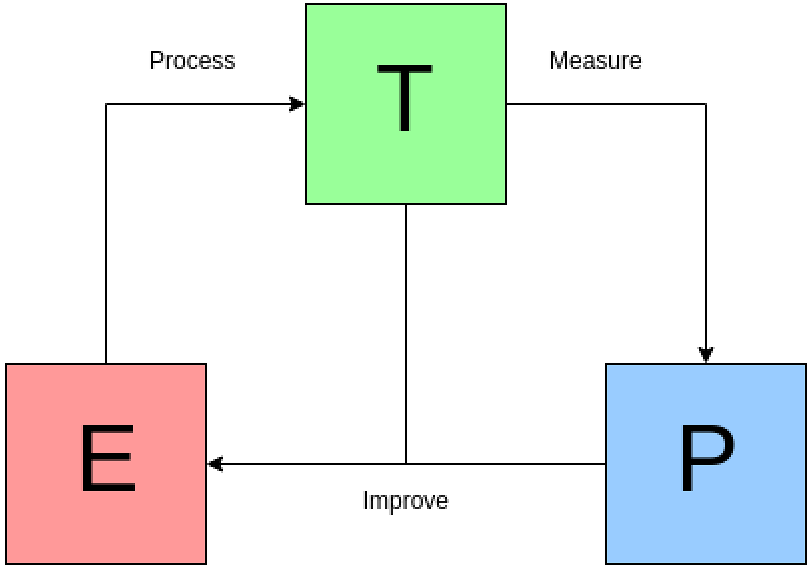
experience E with respect to some class of

tasks T and

performance measure P

if its performance at tasks in T, as measured by P, improves with

experience E."



Machine learning

There are generally three types of machine learning:

(1) supervised learning, → Labelled data

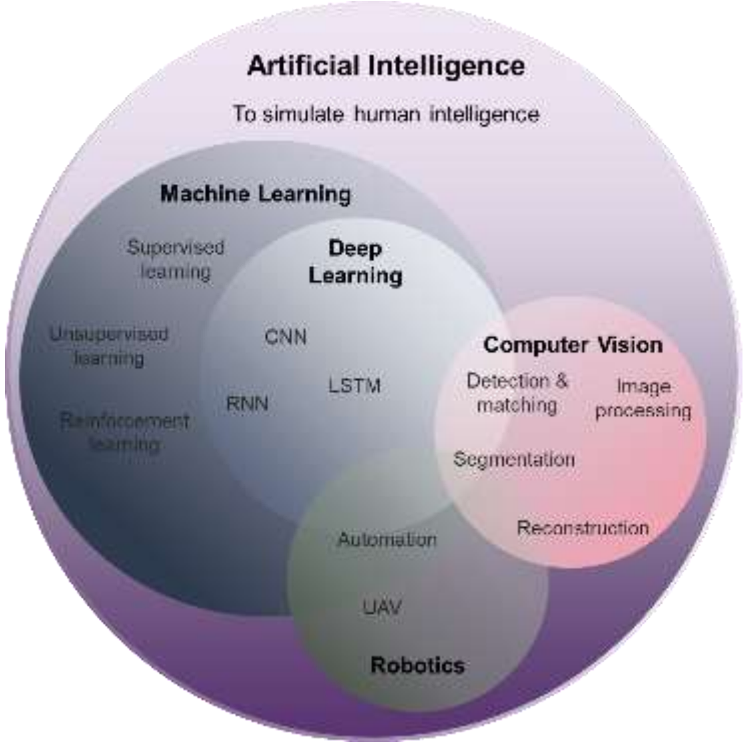
(2) unsupervised learning, and → Unlabelled data

(3) semi-supervised learning → Labelled data / Unlabelled data

Methods for digital assessment of structures

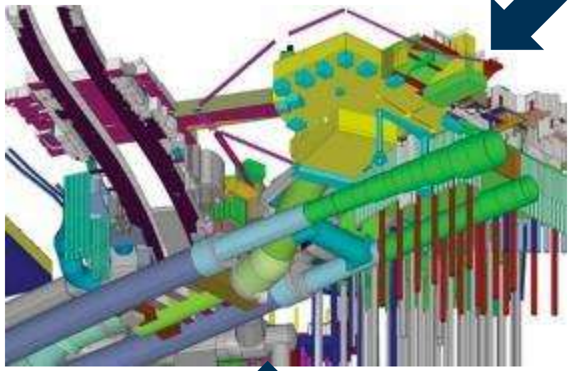
- **Artificial Intelligence (AI)**
  - Computer Vison
  - Machine leering
  - Robotics

- **Building information Modelling (BIM)**



Non-Graphical Data

Graphical Data

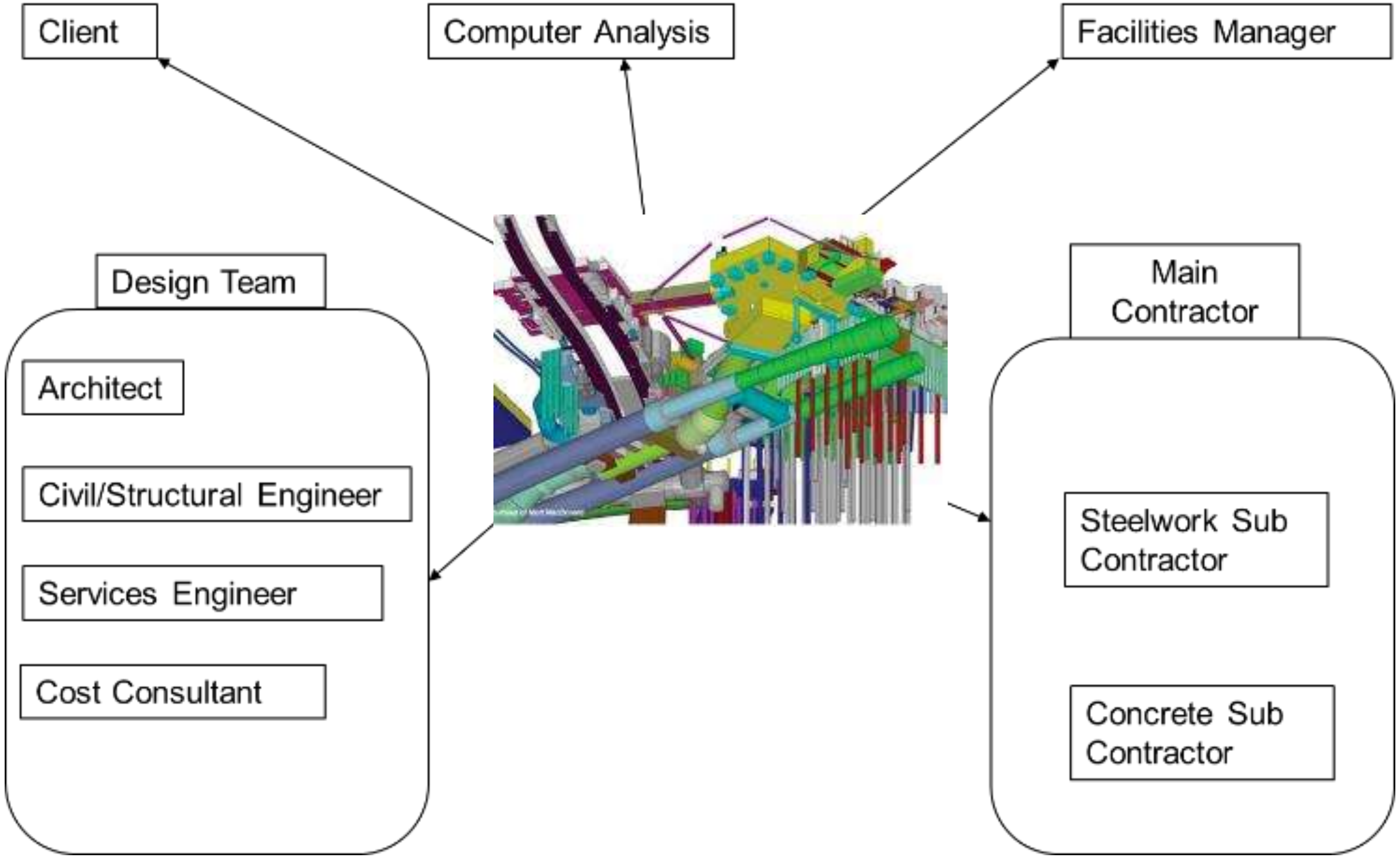


Documents

Building Information Modelling:
"the process of designing, constructing or operating a building or infrastructure asset using electronic object-oriented information" (BS EN ISO 19650-2: 2018)

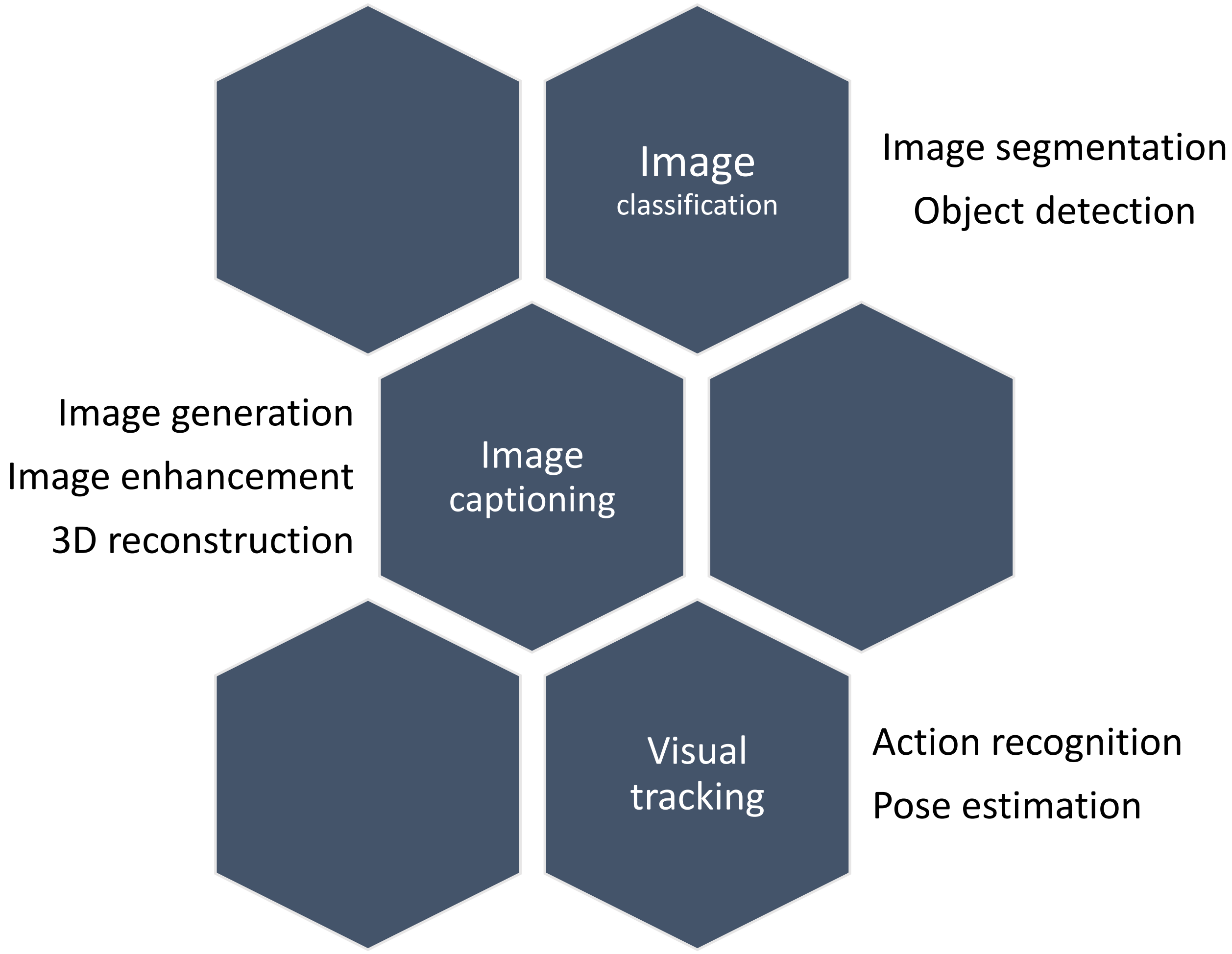
"a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle; defined as existing from earliest conception to demolition." (NBIMS-US™)

BIM collaborative project development



Computer vision tasks and methods

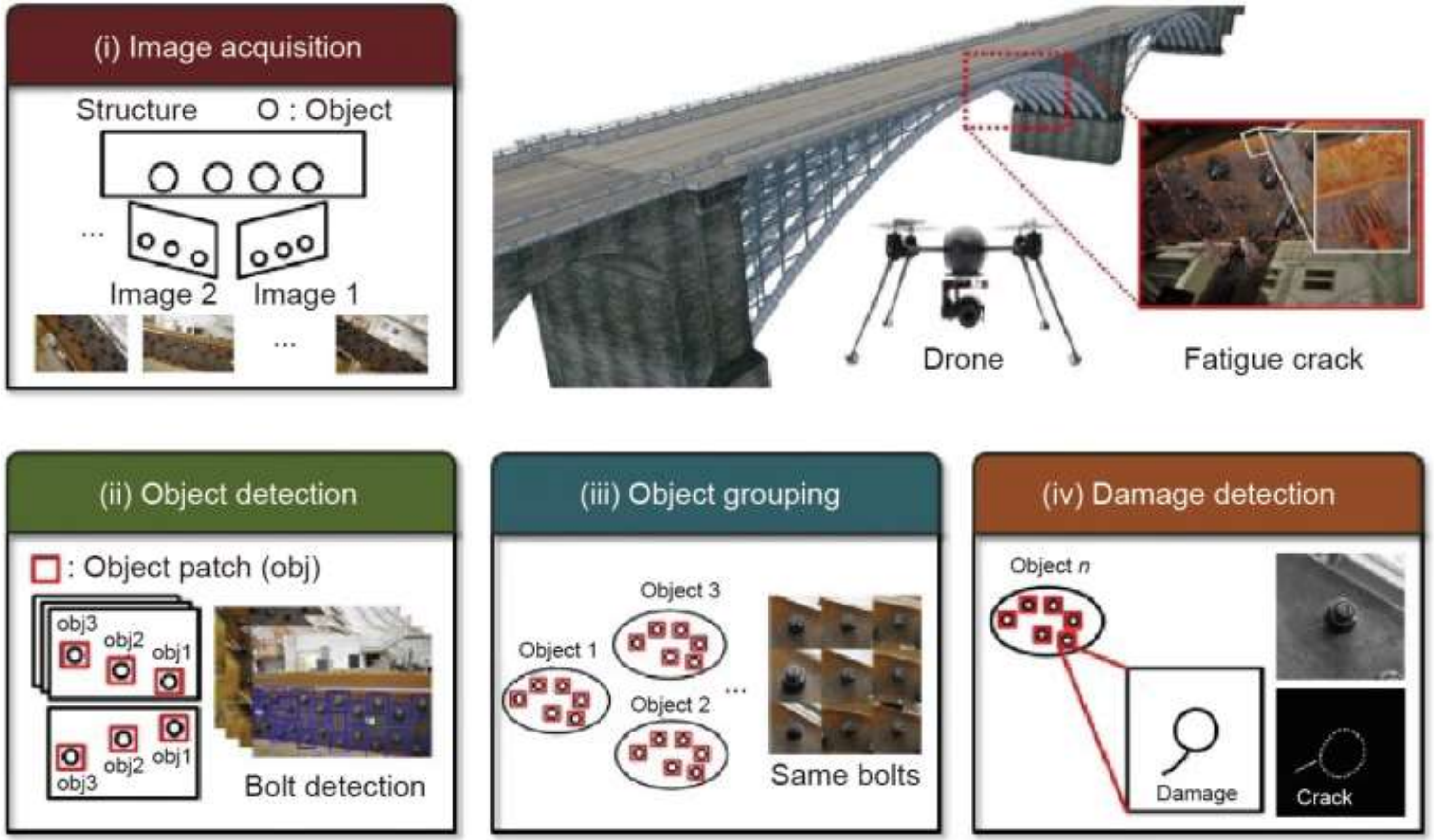
- **CV tasks** refer to the specific objectives or goals that computer vision techniques aim to achieve in the context of infrastructure inspection. These tasks are designed to extract meaningful information from visual data and enable automated analysis and understanding
- **CV methods** refer to the specific techniques and algorithms used to accomplish the computer vision tasks. These methods can vary based on the type of data available, the complexity of the structures, and the specific inspection requirements.



Vision based automatic inspection of bridges

Example of application of Computer Vision methods for inspection and analysis of bridges

- UAV-based image acquisition
- Object detection
- Object grouping and model recontraction
- Condition detection



BIM and DTs

- In general DTs consist of:
  - Physical layer
  - Data transfer, store, management and communicating layer
  - Modelling layer
  - Application layer

- BIM can be:
  - subset of DT (model)
  - or a way to deliver DT

Application layer

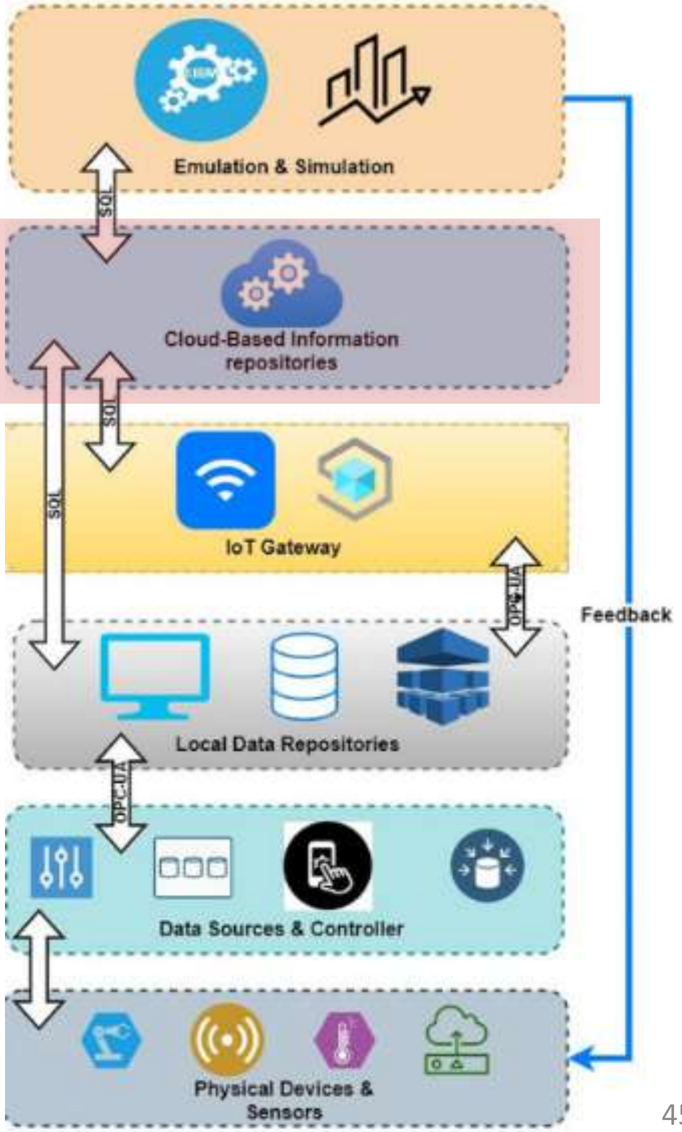
Modelling layer

Communi-cation layer

Data store & management

Data transfer & control

Physical layer



BIM to Digital twins

- Level 1: A static 3D visualization tool, a better information sharing strategy for different stakeholders across the building life cycle;
- Level 2 : BIM-supported simulations based on static project information;
- Level 3: Integration of BIM and IoT techniques, real-time sensor data can be easily obtained and visualized in 3D digital models;
- Level 4: Associated with real-time predictions, by incorporating algorithms, more accurate and reliable decision-making strategies can be obtained automatically or semi-automatically;
- Level 5: Conceptual framework of ideal Digital Twin: automated feedback control for adjustment of parameters:

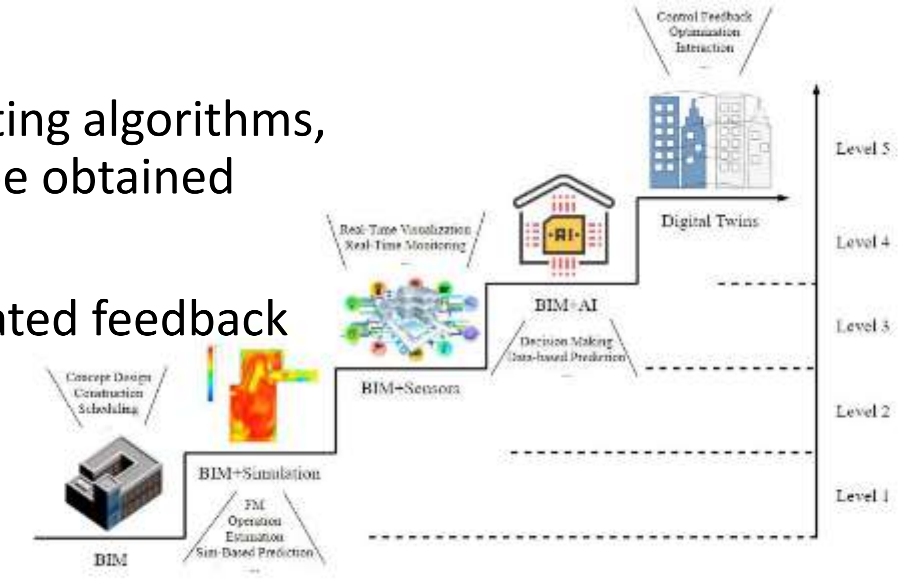
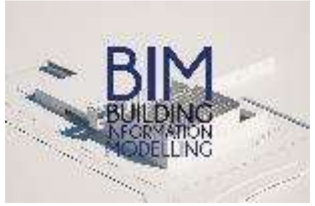


FIG. 1: Evolution of BIM to Digital Twins in the Built Environment

Emerging technologies and digital data



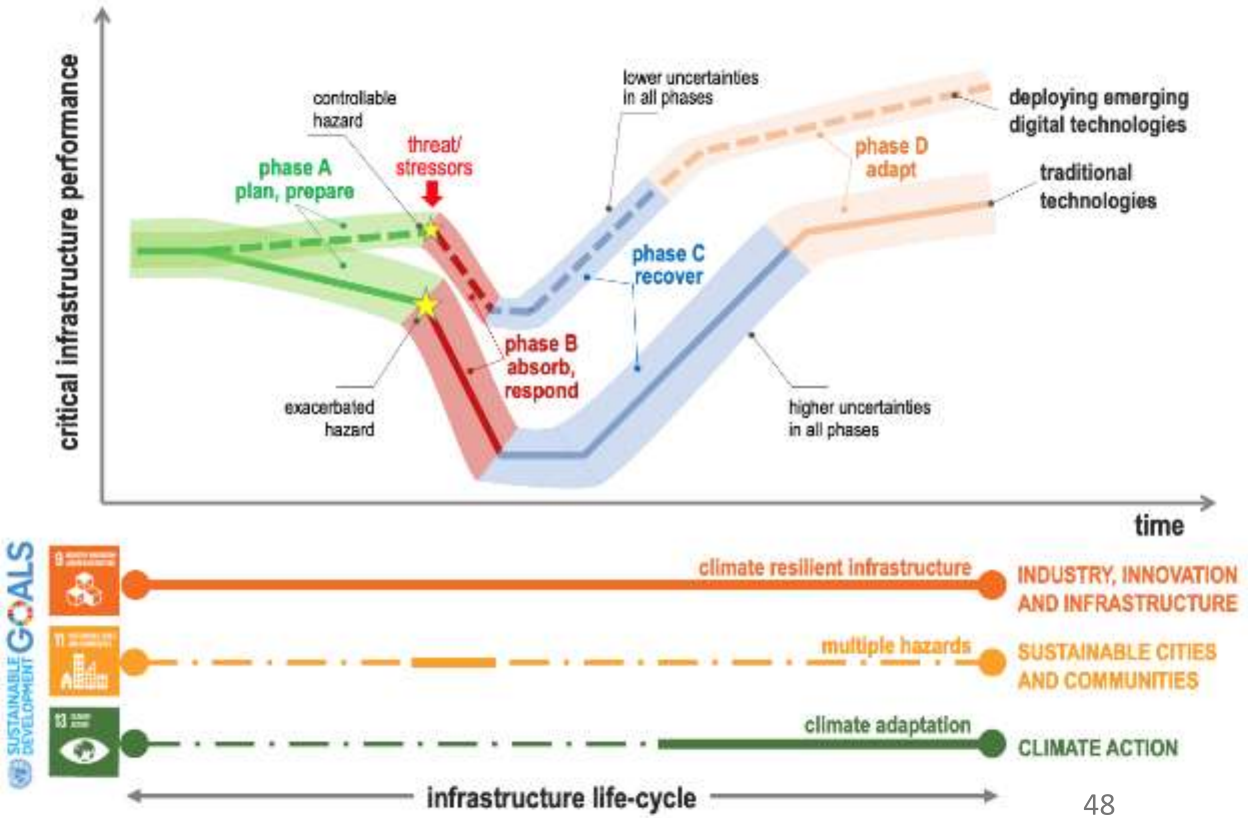
Emerging digital technologies and applications toward climate resilience of infrastructure.

Emerging digital technology	Definition	Examples toward climate resilience
Internet of Things (IoT) (Russell et al., 2018)	The connection over the internet of digital and physical objects, e.g. smartphones, transport infrastructure, energy assets, by means of suitable information exchange, to enable data collection, communication, processing and actionable intelligence for a range of applications, services and decision-making.	***Data collection:*** a cable-stayed bridge is monitored for ice accumulation, temperature variations, and wind loading. ***Communication:*** wireless conveyance of data (internet or other rapid transmissions). ***Processing:*** engineering algorithm and thresholds (**automated performance indicators**). ***Actionable intelligence:*** issue warnings, e.g. reduction of speeds, de-icing systems activated, swift functionality reinstatement.
Artificial Intelligence (AI) and Machine Learning (ML) (Spencer et al., 2019)	Adaptable intellect found in humans, which is simulated by machines, especially computer systems, that can learn and accumulate experience.	Utilizing Unmanned Aerial Vehicles (UAVs) for remote automated data acquisition (videos and photographs) and data processing and inspection using engineering algorithms to interpret the condition of infrastructure such as roads, railways and pipelines (**automation, rapidity**).
Building Information Modelling (BIM) (Davila Delgado et al., 2017)	The information technology for management and exchange of monitoring data, aiming to manage digital representations of all information related to a built asset during its entire life cycle.	***Selection of monitoring systems***, e.g. fibre optics to measure strain and temperature, and photogrammetry to generate point clouds. ***Data processing***, using engineering algorithms and documentation. ***Modelling***, system showing selected monitoring entities and attribute sets. ***Data visualisation and interpretation**, on the* BIM model to gain geometrical context within the infrastructure asset, **rapid data-sharing**.
Digital Twin (DT) (CDBB (Centre for Centre for Digital Built Britain), 2018)	The digital replica of the physical assets, processes, and systems. DT is broader than BIM in the sense that transmits data, monitors the asset in real-time and supports analytics, control and simulation functions by e.g. AI and ML processes.	Same methods as the BIM above, see example on the landmark Polyfytos bridge of Section 4 (Phase A). Combined remote sensing systems are used to update frequently the DT.
Agent-based modelling (ABM) (Dawson et al., 2011; Cimellaro et al., 2019)	A computational model simulating the actions and interactions of autonomous agents, which can be complex infrastructures, individuals or groups, aiming to interpret behaviours based on characteristics and rules, and having the ability to learn and to adapt their behaviours.	ABM evacuation of road networks in the vicinity of coastal areas affected by storm surges could include the following: hazard simulation, agent-based model of human response and travel patterns, traffic simulation, agent vulnerability and risk analysis, congestion warnings and hence enabling **preparedness, rapid quantification of vulnerability/ losses** and **recovery**.

Argyroudis, Mitoulis et al. (2022)

Digitalisation in critical infrastructure management

		emerging technologies enhancing different phases of the life-cycle climate resilience		
phase of resilience	**traditional management ramifications**	**emerging digital technology**		**resilience enhancement - example**
A plan prepare	climate change leading to decrease of performance | reduced knowledge of ageing, accelerated deterioration, increased demand	building information modelling (BIM) | digital twins | data analytics | machine learning & artificial intelligence (AI) | agent-based modelling	5G | internet of things (IoT) | structural health monitoring (SHM)	climate preparedness, including the impact of multiple stressors | better understanding of interdependencies | accurate evaluation of infrastructure exposure | update of hazard models
B absorb respond	excessive losses due to inadequate preparedness and high vulnerabilities	phone metadata | crowdsourcing| social media | data analytics | unmanned aerial vehicle (UAV)| light detection and ranging (LiDAR)		reduced losses due to early warnings or monitoring of interoperabilities
C recover	delayed commencement of recovery due to uncertainties in understanding asset condition | slow recovery due to inefficient prioritization and allocation of resources	UAV | LiDAR | satellites | aerial imagery | machine learning & AI		smaller idle time due to rapid post-disaster assessment | fast recovery by guiding response | drones using machine learning for damage detection
D adapt	inadequate information for asset performance and interdependencies | subjective allocation of resources	agent-based modelling | augmented and mixed reality | sensors from connected vehicles		data-driven adaptation enhanced by innovative/sustainable solutions | monitoring of infrastructural, technological, social, informational, and environmental interdependencies | prevent cascading threats



Climate resilience of infrastructure enhanced by emerging digital technologies versus traditional management using conventional approaches.

ReCharged UNIVERSITY OF BIRMINGHAM

Your experience in digitalisation

Reflection:

- Think about an occasion of your life where you considered digital technologies. What is your experience?
- In you experience how digital data and digitalisation will help the engineer to make decisions more efficiently ?

The lecture had the following learning outcomes

- Defined resilience and its properties for critical infrastructure assets, networks and systems.
- Defined sustainability and its properties for critical infrastructures assets, networks and systems.
- Explained the importance of digitalisation and its applicability for enhancing resilience and sustainability of critical infrastructure assets, networks and systems.