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

Lecture 1 Introduction to Resilience, Sustainability and Digitalisation of critical infrastructure systems

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 1-Week 1

The aim of this week is to introduce the concepts of resilience, sustainability and digitalisation in the critical infrastructure sector. This includes adaptation and responsiveness to climate change and other natural and human-induced shocks, resource efficiency, minimised environmental impact, social inclusivity, long-term planning, economic viability, and governance towards an efficient lifecycle management. Week 1 will also introduce the use of digital and emerging technologies for enhancing the modelling, assessment, and delivery of more resilient and sustainable critical infrastructure to assist decision makers and make people feel safer and included.

- 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.

Lecture 1. Introduction to Resilience, Sustainability and Digitalisation of critical infrastructure systems

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. Learning Outcomes as discussed briefly last week, but feel free to amend.

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?

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To effectively serve our communities, infrastructure needs to be resilient to an evolving world while efficiently utilising limited resources in a sustainable way. Research and investment in sustainability, resilience and digitalisation are rapidly expanding, with substantial efforts underway at many institutions, research centres and industries globally. The aim of this week is to introduce the concepts of resilience, sustainability, and digitalization in the critical infrastructure sector.

Activity 1. What is Resilience?

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, *Sylua Syluarum* §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

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The history of resilience: from economy to engineering

OED | Oxford English Dictionary

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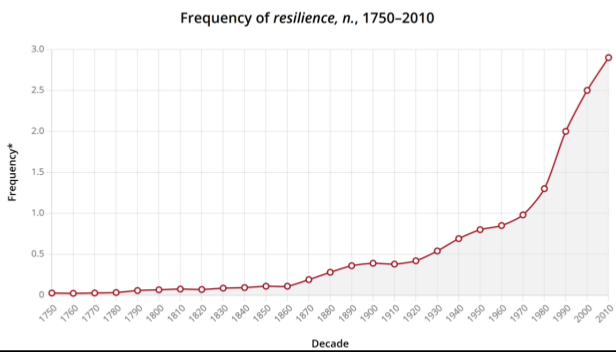
The action or an act of rebounding or springing back; rebound, recoil.

Elasticity; the power of resuming an original shape or position after compression, bending, etc.



* Occurrences per million words in written English

The word "resilience" originates from the Latin term "*resilire*," which means "to leap back" or "to rebound." The term first entered the English language in the 17th century, with its earliest recorded use in 1626. It initially had a physical connotation, describing the ability of a material to spring back into shape after deformation. The Oxford English Dictionary (OED) defines "resilience" as the capacity to recover quickly from difficulties or the ability of a substance or object to spring back into shape. Over time, the term's usage expanded from its original physical context to include psychological and systemic aspects, such as the resilience of individuals, communities, economies, and ecosystems. The term "resilience" has seen a significant evolution from 1750 to the present. Early usage was relatively rare, primarily confined to discussions in physics and engineering. However, its frequency began to increase in the 20th century as the concept was adopted by various disciplines.

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.

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The concept of resilience has evolved significantly over time, originating in the field of ecology and later being adopted by various disciplines, including economics and engineering. In the 1970s, ecologist C.S. Holling introduced the idea of resilience to describe the capacity of ecosystems to absorb disturbances and still maintain their essential functions and structures. This ecological perspective emphasized the dynamic nature of systems and their ability to adapt to changing conditions. The concept soon migrated to economics, where it was used to describe the ability of economies to withstand and recover from shocks, such as financial crises or natural disasters. Economic resilience focuses on the mechanisms and policies that enable economies to bounce back and sustain growth despite adverse conditions. In the field of engineering, resilience has become a critical framework for designing and managing infrastructure systems. Engineering resilience emphasizes the robustness, redundancy, and adaptability of infrastructure to withstand and quickly recover from disruptions, such as extreme weather events, earthquakes, or human-made hazards. This approach seeks to ensure that critical infrastructure, such as transportation networks, energy grids, and water systems, remains functional and reliable under a wide range of conditions.

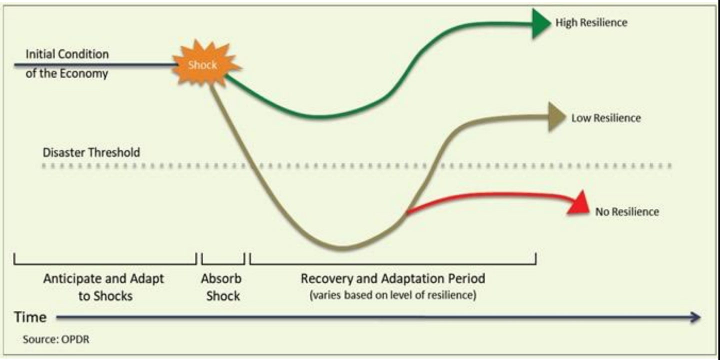
The history of resilience: from economy to engineering

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

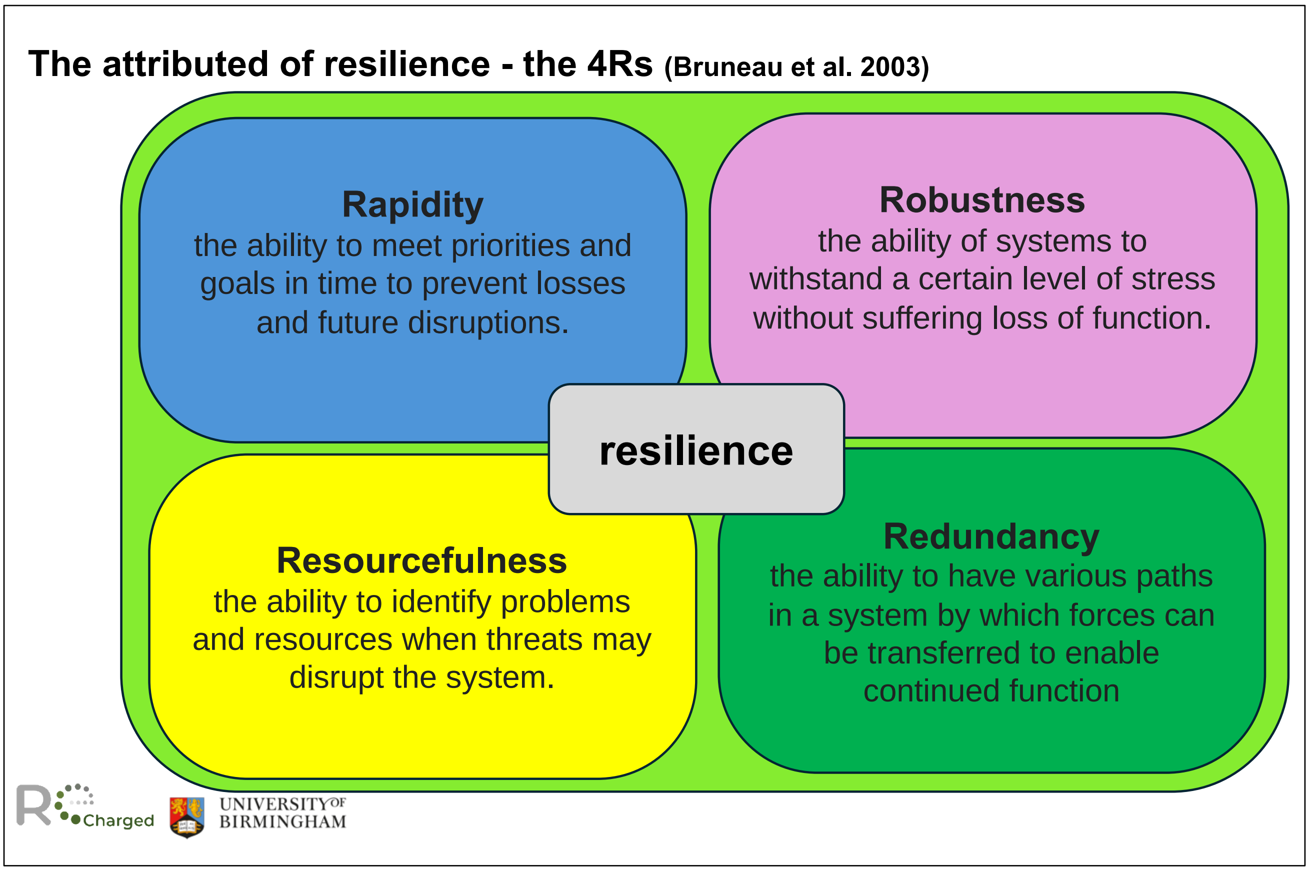
Resilience in economy includes two key components *(Hallegatte 2014)*.
1. the ability of an **economy as a whole** to cope, recover from and reconstruct after a shock;
2. the resilience of **individual households or firms**, and their ability to cope with or recover from a shock and adapt to changing 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.

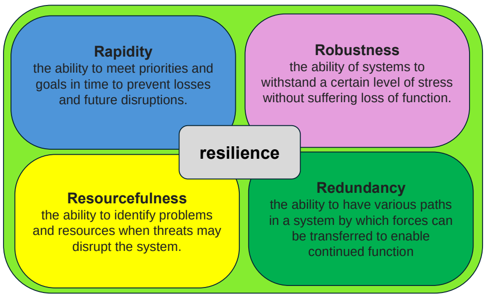


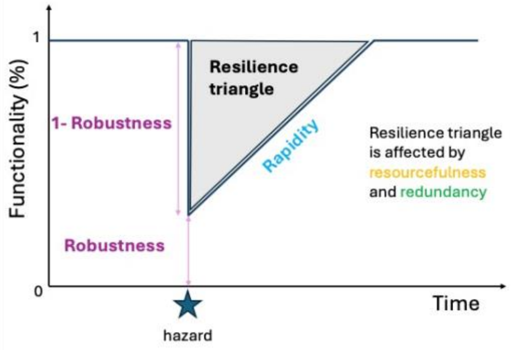
Economic resilience has two distinct but overlapping definitions (Hallegatte, 2014). Broadly, it refers to an economy's ability to cope, recover, and rebuild after a shock. It also pertains to the resilience of individual households or firms, their capacity to cope with or recover from shocks, and adapt to changing economic circumstances. This includes the distributional effects of a shock, individual vulnerability, and existing welfare provisions. These concepts are interrelated, as each can influence and depend on the other. Central to this notion is minimising aggregate welfare losses. Higher economic resilience means lower economic losses from a shock over time. Alternatively, resilience can also promote welfare gains, as seen in development economics, which posits that strengthening the economic assets of individuals and communities enhances their resilience to economic shocks. Economic resilience includes two key components. First, the ability of households, firms, or an economy to withstand or absorb an economic shock. Second, a dynamic component involves the ability to adapt to changing circumstances and strengthen responses to future shocks. While much of our understanding of economic resilience focuses on available assets (financial, physical, and social capital), there is growing recognition of the role of choices and the ability to make and act on these choices in influencing resilience outcomes.



A common definition of resilience is based on the 4Rs, introduced by Bruneau et al. (2003):
Rapidity: *the ability to meet priorities and goals in time to prevent losses and future disruptions*. For example, in the case of a major power outage, a resilient electricity grid can quickly restore power to critical facilities, such as hospitals, within hours, preventing disruptions to essential medical services and ensuring that life-saving equipment remains operational.
Robustness: *the ability of systems to withstand a certain level of stress without suffering loss of function*. For example, robust bridges are designed to withstand extreme flood actions and/or seismic activity. Bridges that have been retrofitted with advanced materials and engineering techniques to endure extreme dynamic loads and water pressures, ensuring that it remains functional during and after hazard event.
Redundancy: *the ability to have various paths in a system by which forces can be transferred to enable continued function*. For example, A water supply network with multiple pipelines and pumping stations can reroute water if one pipeline fails. Thus, a water supply system includes multiple aqueducts and reservoirs, ensuring that water can be redirected if a primary source is compromised is considered redundant and hence resilient.
Resourcefulness: the ability to identify problems and resources when threats may disrupt the system. For example, during the COVID-19 pandemic, resourceful transportation systems quickly adapted by reallocating buses and trains to meet changing demands, implementing safety measures, and creating dedicated routes for essential workers.

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

Resilience is typically defined by the area under the functionality curve normalized by reference time, which is often arbitrarily assumed. This dimensionless quantity is referred to as resilience index. A simplified functionality curves is represented by the resilience triangle, assuming a linear recovery of the functionality after the hazard event. The remaining functionality after the hazard event represents the robustness of the infrastructure. The slope of the recovery represents the ‘rapidity’. The shape of this triangle is affected by the resourcefulness and redundancy.

Resilience can be understood and enhanced at various scales, ranging from individual components to international systems. Two complementary approaches to conceptualising resilience across these scales are considered:

Bottom-Up Approach:

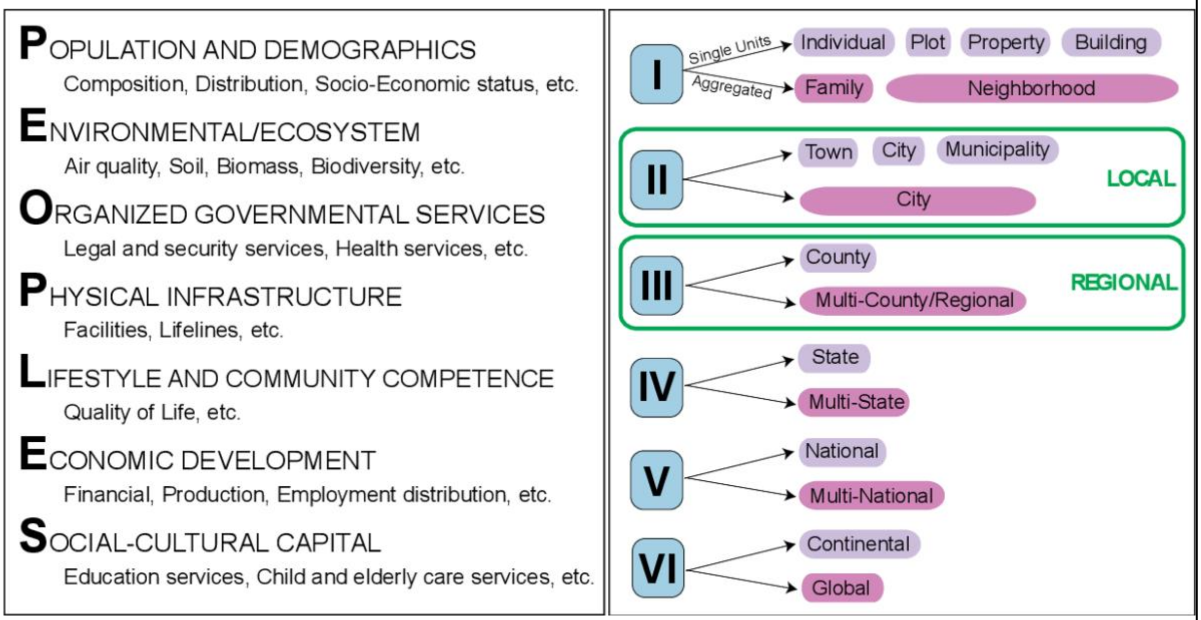
1. **Component**: The smallest, fundamental units of infrastructure, such as a single bridge pier or a segment of a pipeline.
2. **Asset**: Individual infrastructure assets, like a bridge or a power plant, composed of various components.
3. **Network**: Networks of interconnected assets, such as transportation networks or power grids.
4. **System**: Integrated systems of networks, like an entire transportation system or an electrical grid system.
5. **System of Systems**: Interconnected systems that collectively provide broad functionality, such as urban infrastructure systems combining transportation, water, and energy systems.
6. **Regional**: Regional infrastructure systems that provide services across cities or districts.
7. **National**: National-level infrastructure systems that integrate regional systems and networks, ensuring nationwide service continuity.
8. **International**: Global infrastructure networks and systems, such as international supply chains or transnational power grids.

Top-Down Approach:

1. **International**: Global frameworks and agreements that guide national and regional resilience strategies.
2. **National**: National policies and infrastructures that align with international standards and ensure resilience across regions.

3. **Regional**: Regional coordination and infrastructure systems that adhere to national guidelines and support local resilience.
4. **System of Systems**: Overarching systems that integrate multiple systems within a region or nation to provide comprehensive resilience.
5. **System**: Individual systems within the system of systems, optimized for resilience at their level of operation.
6. **Network**: Specific networks within each system, ensuring that individual networks are resilient and interconnected.
7. **Asset**: The assets within each network that are designed and maintained for resilience.
8. **Component**: The fundamental components that make up each asset, designed to withstand stress and recover quickly from disruptions.

The dimensions of resilience



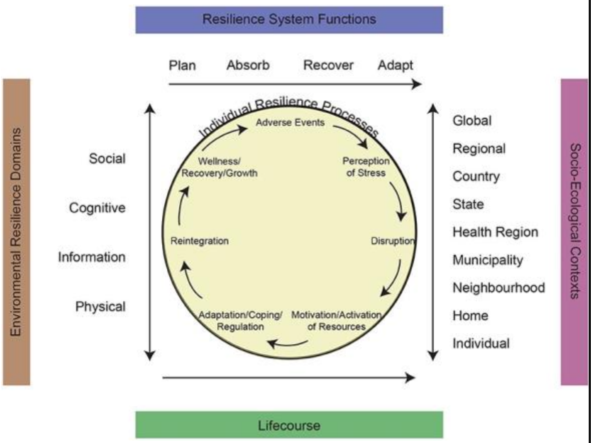
The PEOPLES Resilience Framework and associated Geographic Scales (Renschler et al. 2010)

A well-known resilience framework is the PEOPLES framework for measuring community resilience at different spatial and temporal scales (Renschler et al., 2010). Seven dimensions are identified for measuring the community resilience: Population and Demographics, Environmental/Ecosystem, Organized Governmental Services, Physical Infrastructures, Lifestyle and Community Competence, Economic Development, and Social-Cultural Capital. They are summarised with the acronym PEOPLES. Each dimension is characterised by a corresponding performance metric that is combined with the other dimensions using a multi-layered approach. Therefore, once a hybrid model of the community is defined, the proposed framework can be applied to measure its performance against any type of extreme event during emergency and in long term post-disaster phases. A resilience index can be determined to reflect all, or part, of the dimensions influencing the events.

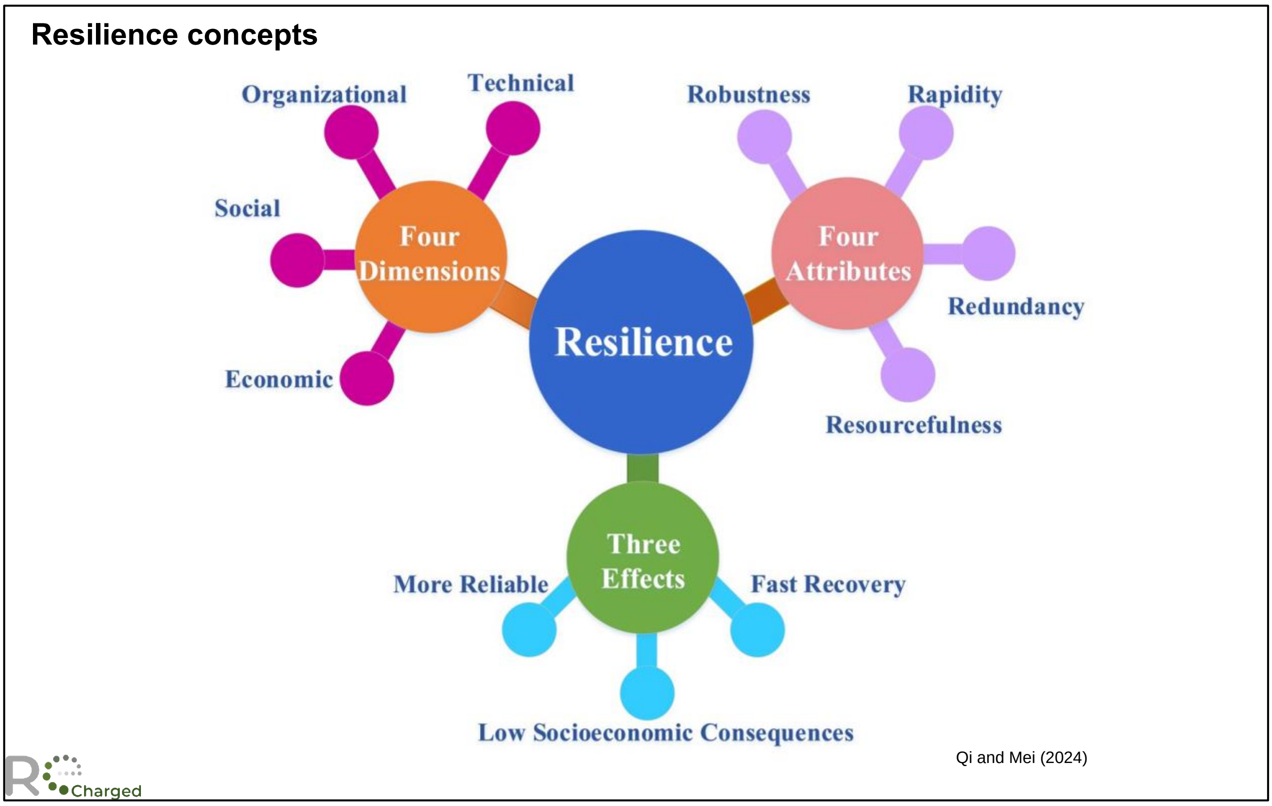
The PEOPLES Resilience Framework is built on, and expands, previous research at MCEER linking several previously identified resilience dimensions (i.e., technical, organizational, societal, and economic) and resilience properties (i.e., R4: robustness, redundancy, resourcefulness, and rapidity) (Bruneau et al., 2003). PEOPLES incorporates MCEER's widely accepted definitions of service functionality, its components (assets, services, demographics) and the parameters influencing their integrity and resilience. While the components have different weights and values, the order of these dimensions in the acronym is not indicative to their importance.

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



The main domains of resilience include the following (Wister et al., 2022):
(1) **Social resilience** refers to maintaining positive social interactions, such as community participation and social engagement. In contrast, significant social isolation can lead to negative adaptations to adversity, particularly in old age.
(2) **Cognitive resilience** involves the ability to cope with stressors arising from adversity. This includes understanding one's baseline health and needs, though mental health conditions or dementia can impede necessary behavioral changes to adapt to adverse events.
(3) **Information resilience** emphasizes the importance of literacy, knowledge, and access to information resources that enhance understanding of resilience pathways and solutions to adverse events. It encompasses an individual's competence, literacy level, and access to information needed to make resilient decisions in their environment.
(4) **Functional resilience** pertains to the interconnection between an individual and their environment at genetic, physiological, and functional levels. It reflects one's ability to complete daily tasks, fulfill social roles, and remain functionally active within their environment.
These resilience domains uniquely and interactively affect outcomes in the face of adversity.

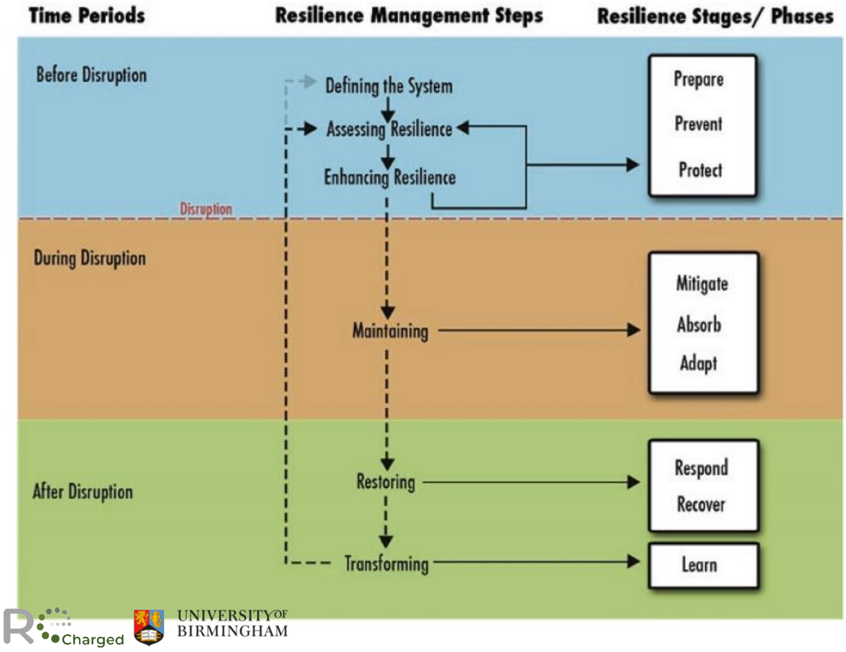


Resilience of critical infrastructure is described by various dimensions, attributes, and effects.
The **four dimensions** of resilience**,** include the following:
Organizational: Refers to the ability of institutions and organisations to manage and coordinate efforts to enhance resilience. **Technical**: Encompasses the engineering and technological aspects that contribute to the robustness and adaptability of infrastructure systems. **Social**: Involves community engagement, social networks, and the capacity of individuals and communities to support each other during and after disruptions. **Economic**: Pertains to the financial resources and economic strategies that support resilience, including funding for mitigation and recovery efforts.

The **four attributes** of resilience (see also previous slide):
Robustness: The strength and durability of infrastructure systems to withstand stress without losing functionality. **Rapidity**: The speed at which systems can respond to and recover from disruptions, minimising downtime and future disruptions. **Redundancy**: The availability of alternative pathways and backup systems that ensure continuous operation when primary systems fail. **Resourcefulness**: The ability to identify problems, allocate resources efficiently, and implement effective solutions during and after adverse events.

The **three effects** of resilience:
More Reliable: Ensures that infrastructure systems are dependable and consistently operational, even under stress. **Fast Recovery**: The ability of systems to quickly return to normal or near-normal functionality following a disruption. **Low socioeconomic consequences**: Minimises the economic and social impacts of disruptions, reducing the overall burden on communities and economies.
Hence, resilience in critical infrastructure is multifaceted, involving a blend of organisational, technical, social, and economic elements. By integrating these dimensions and attributes, we can achieve more reliable systems, faster recovery times, and lower socioeconomic consequences, ultimately enhancing the resilience of our critical infrastructure.

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 systems refers to the ability of an organisation, infrastructure, or community to withstand, adapt to, and recover from disruptions. These disruptions can be anything from natural disasters, economic crises, technological failures, to social upheavals. The role of resilience is critical in ensuring that systems not only survive these disruptions but also continue to function and improve over time. The main resilience-based management steps with respect to the resilience phases include the following:

Before Disruption:

Defining Resilience: The initial step involves understanding what resilience means for a particular system. This includes identifying potential threats, vulnerabilities, and the critical functions that need to be protected. **Assessing Resilience:** This step involves evaluating the current state of the system's resilience. This can be done through risk assessments, stress testing, and scenario planning to identify gaps and weaknesses. **Enhancing Resilience:** Based on the assessment, strategies and measures are implemented to strengthen the system. This may include building redundancies, diversifying resources, and improving communication and coordination mechanisms.

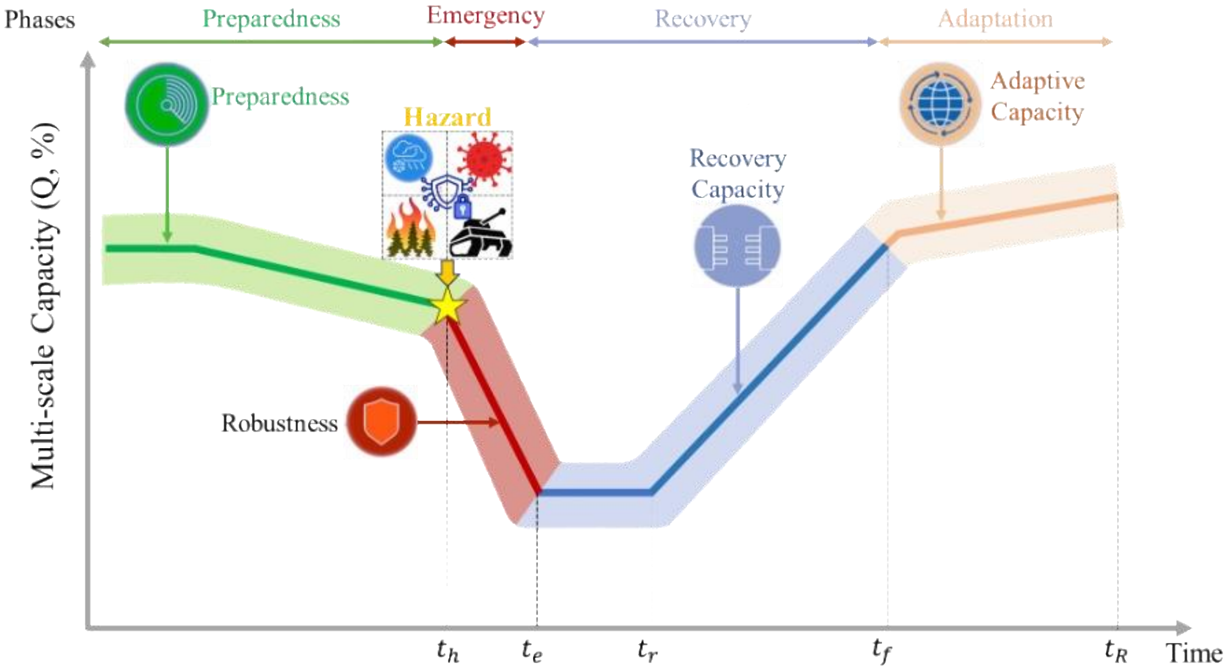
During Disruption:

Maintaining resilience, i.e. Mitigating: During a disruption, the immediate focus is on mitigating the impact. This involves activating emergency plans, safeguarding critical functions, and ensuring the safety of people and assets. **Absorbing:** This refers to the system's ability to absorb the shock without significant breakdowns. Effective buffering mechanisms, such as backup systems and contingency plans, play a crucial role here. **Adapting:** As the disruption unfolds, the system must adapt to changing conditions. This involves real-time decision-making, reallocating resources, and modifying operations to maintain functionality.

After Disruption:

Responding: Once the immediate threat has passed, the response phase involves actions to stabilize the system. This includes restoring essential services, providing support to affected individuals, and initiating recovery efforts. **Recovering:** The recovery phase focuses on returning the system to its normal or an improved state. This can involve repairing damage, rebuilding infrastructure, and restoring economic and social activities. **Transforming and Learning:** Finally, the system should transform based on lessons learned from the disruption. This involves analysing what happened, understanding the effectiveness of the response, and implementing changes to improve future resilience. Continuous learning and improvement are crucial to evolve and enhance the system's ability to handle future disruptions.

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

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Infrastructure resilience can be represented through four distinct phases of the infrastructure life-cycle (Argyroudis et al., 2022). These phases include planning and preparation before the hazard events (preparedness), absorption and response during and immediately after the hazard occurrence (emergency), followed by recovery and adaptation to novel stressors. The planning and preparedness phase , represent infrastructure performance for normal conditions, during which a gradual loss of operability ensues, e.g. due to ageing effects and asset deterioration. The phase of absorption and response of phase are illustrated by the loss of functionality due to hazard events. The recovery phase of the infrastructure functionality includes the restoration of capacity and reinstatement of the operation. The adaptation phase D concerns future stressors, e.g. novel loads, climatically exacerbated hazards, which may take place before or after a hazard event.

Reflection:

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

What is your experience?

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Activity 2. What is Sustainability?

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?

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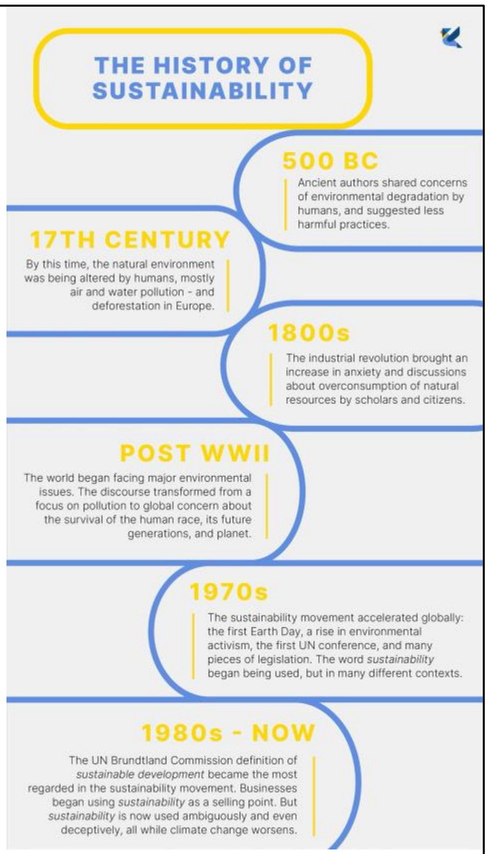


Source: thesustainableagency

The four pillars of sustainability include the following:

- **Human:** Emphasizes the importance of human well-being and ensuring that practices benefit people.
- **Social:** Focuses on maintaining social equity, cultural cohesion, and community resilience.
- **Economic:** Highlights the need for economic systems to be efficient, profitable, and equitable.
- **Environmental:** Stresses the importance of protecting the natural environment and promoting ecological health.

The timeline of “Sustainability”

- **500 BC:** Ancient authors expressed concerns about environmental degradation and recommended less harmful practices.
- **17th Century:** Human activities, particularly air and water pollution and deforestation in Europe, began to significantly alter the natural environment.
- **1800s:** The Industrial Revolution led to increased anxiety and discussions about the overconsumption of natural resources among scholars and citizens.
- **Post-WWII:** The world started facing major environmental issues, shifting the discourse from local pollution to global concerns about the survival of humanity, future generations, and the planet.
- **1970s:** The sustainability movement gained global traction, marked by the first Earth Day, environmental activism, and international conferences like the UN Conference. The term "sustainability" began to be widely used in various contexts.
- **1980s - Now:** The UN Brundtland Commission provided a widely accepted definition of sustainable development. However, while sustainability became a mainstream concept, it has often been used as a marketing tool, sometimes misleadingly, even as global climate challenges intensify.

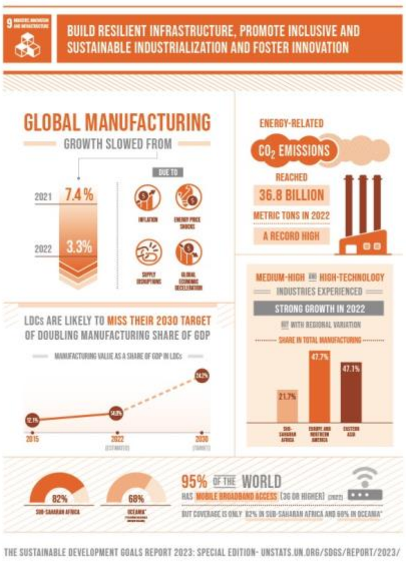
Sustainable Development Goals and policies

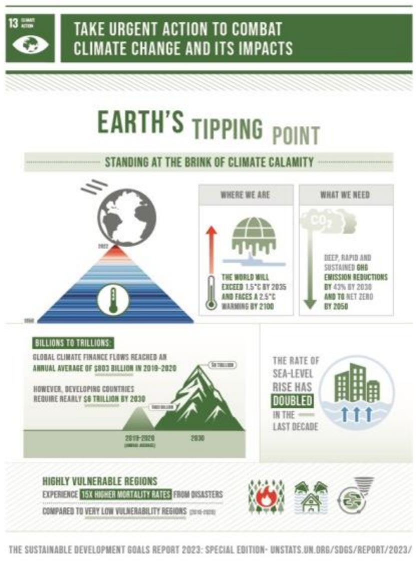
The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, provides a shared blueprint for peace and prosperity for people and the planet, now and into the future.

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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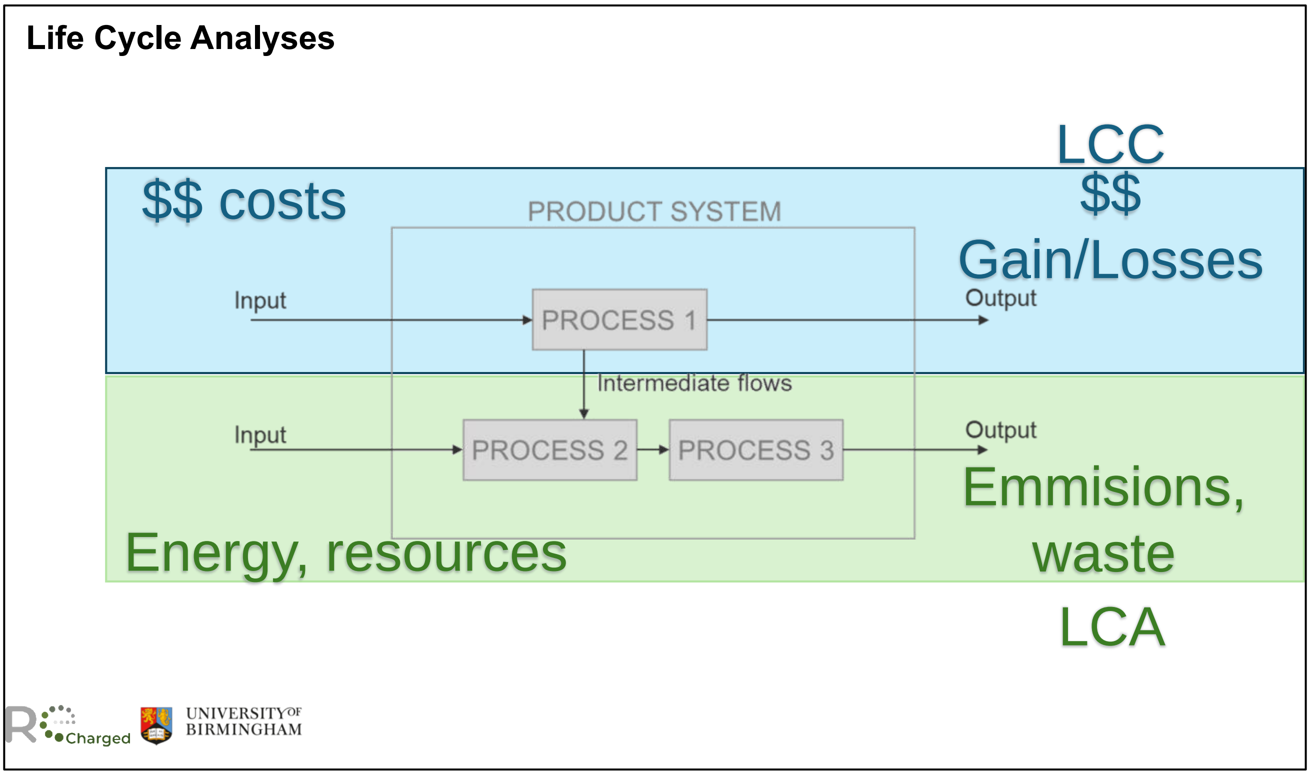
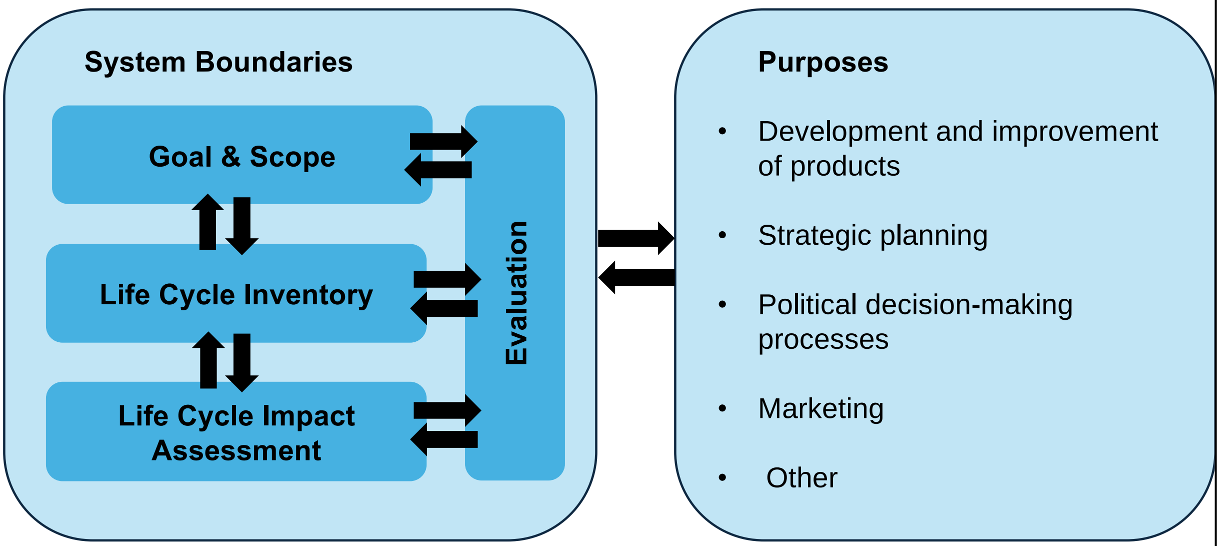
More details on SDGs can be found here: https://sdgs.un.org/goals and here: https://youtu.be/zF361a019zA



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."



This figure outlines the **Life Cycle Assessment (LCA) process** within specified **system boundaries** and its various **purposes**.

LCA Process within System Boundaries

Goal & Scope: This is the initial phase where the objectives of the LCA study are defined, and the scope is determined. It sets the framework for the entire assessment, including the system boundaries, assumptions, and limitations.

Life Cycle Inventory: This phase involves collecting data on all the inputs (e.g., energy, materials) and outputs (e.g., emissions, waste) throughout the product's life cycle. It is a detailed accounting of the resources used and the environmental releases associated with the product.

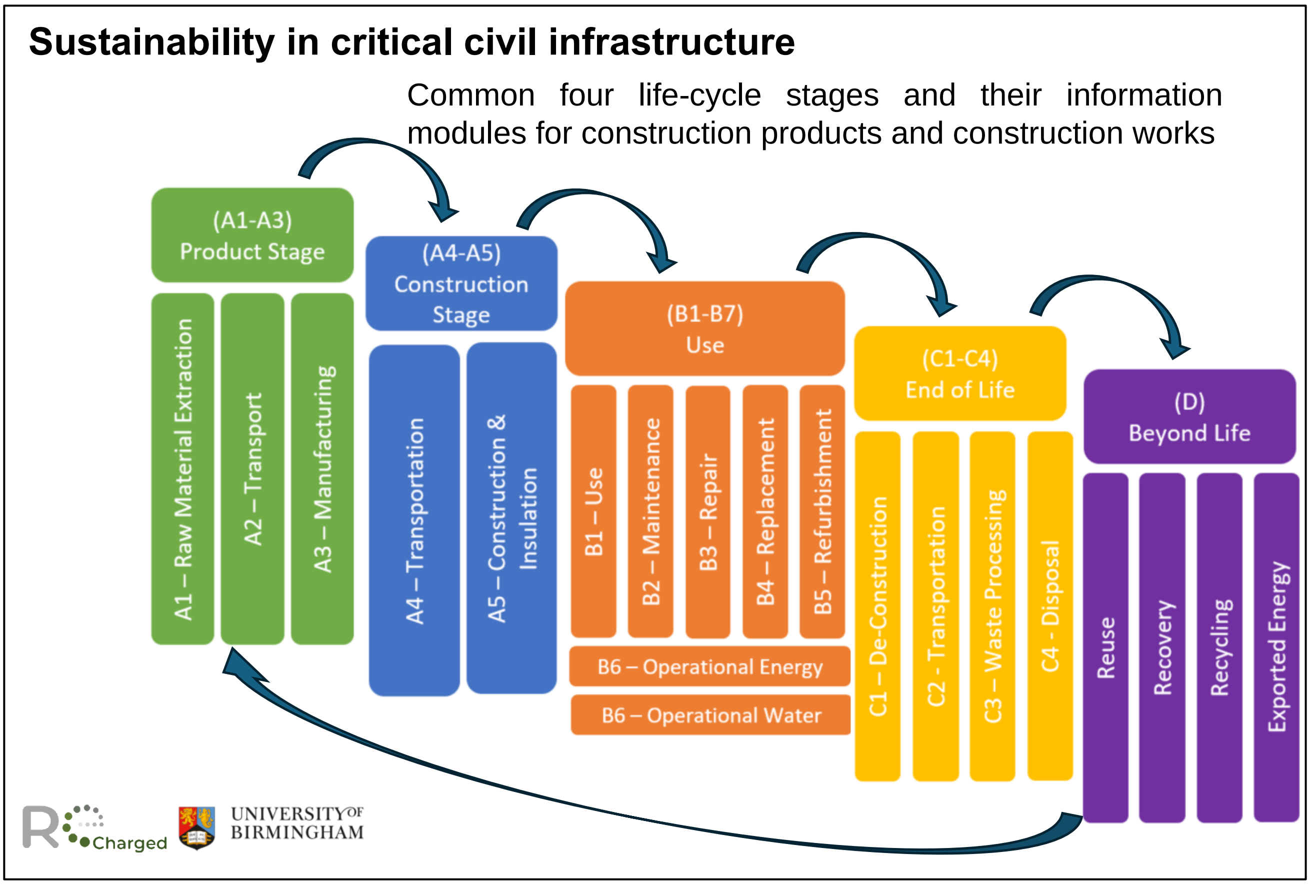
Life Cycle Impact Assessment: In this phase, the data from the inventory is analyzed to assess the potential environmental impacts. This includes evaluating impacts on human health, ecosystems, and resource depletion.

Evaluation: At each stage, there is an evaluation process where results are analyzed and interpreted to understand the environmental performance of the product or system.

Purposes of LCA

Development and improvement of products: LCA helps in enhancing product designs by identifying opportunities for reducing environmental impacts.

- **Strategic planning:** Organizations use LCA for long-term planning, especially in making decisions that align with sustainability goals.
- **Political decision-making processes:** Governments and policymakers utilize LCA to inform regulations and policies that aim to reduce environmental impacts at a societal level.
- **Marketing:** Companies may use LCA results to support environmental claims about their products, enhancing their market position.
- **Other:** LCA can also be applied to various other purposes depending on the specific needs and objectives of the study.



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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This figure provides a comprehensive overview of the life cycle of a product, emphasizing the interconnectedness of each stage and the importance of considering the entire lifecycle when evaluating sustainability.

The stages are broken down into five main phases, each consisting of various sub-processes:

1. Product Stage (A1-A3)

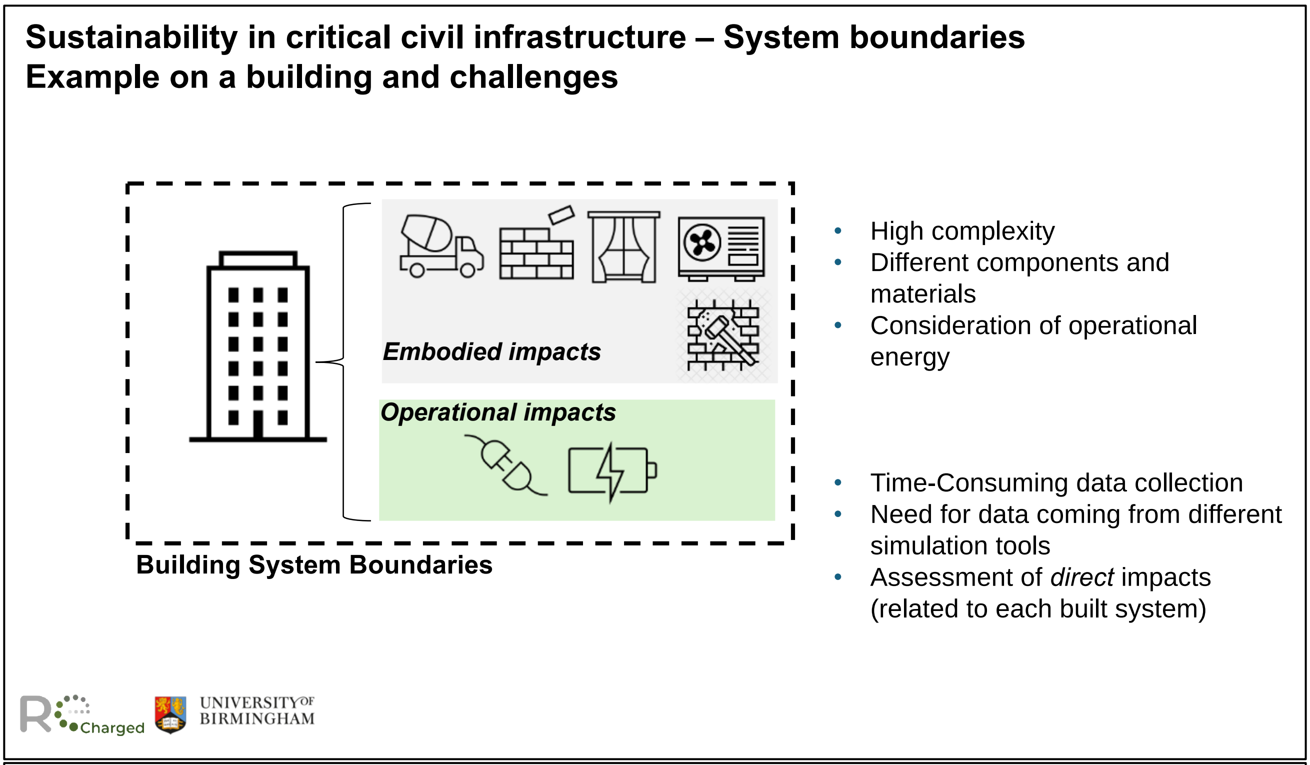
A1 – Raw Material Extraction: The process of extracting raw materials required for the product.

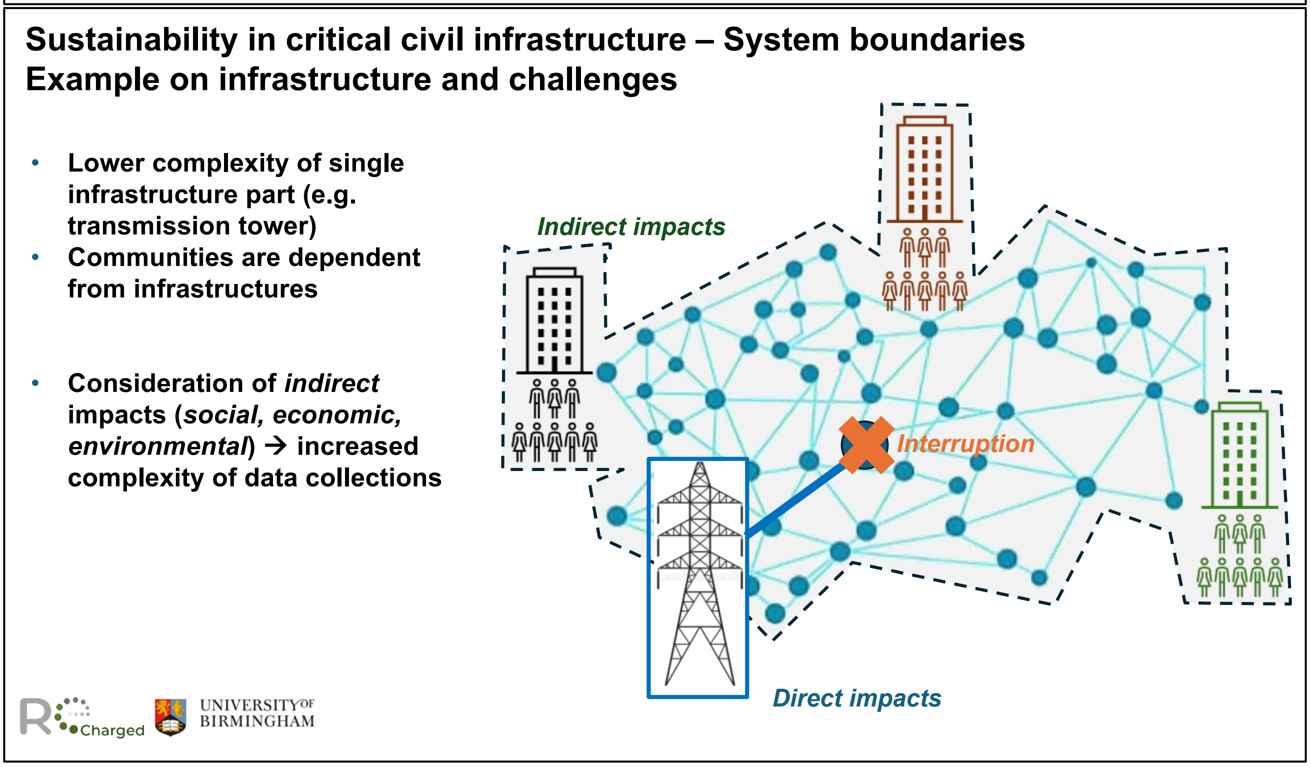
A2 – Transport: The transportation of raw materials to the manufacturing site.

A3 – Manufacturing: The process of turning raw materials into the final product.
2. Construction Stage (A4-A5)
A4 – Transportation: Transporting the finished product to the construction site.
A5 – Construction & Installation: The actual construction or installation of the product.
3. Use Stage (B1-B7)
B1 – Use: The product being in use.
B2 – Maintenance: Regular maintenance to ensure the product's functionality.
B3 – Repair: Repairing the product if it breaks down or is damaged.
B4 – Replacement: Replacing parts or the entire product as needed.
B5 – Refurbishment: Upgrading or refurbishing the product.
B6 – Operational Energy: Energy consumption during the product's use phase.
B6 – Operational Water: Water consumption during the product's use phase.
4. End of Life Stage (C1-C4)
C1 – Deconstruction: The process of taking apart the product after its useful life.
C2 – Transportation: Transporting the deconstructed parts for processing or disposal.
C3 – Waste Processing: Handling waste materials from deconstruction.
C4 – Disposal: Final disposal of waste that cannot be reused or recycled.
5. Beyond Life Stage (D)
Reuse: Repurposing parts of the product.
Recovery: Recovering materials or energy from the product.
Recycling: Recycling materials to be used in new products.
Exported Energy: Energy recovery from waste materials, often through incineration.

The diagram shows arrows flowing from one stage to the next, highlighting the progression of the product's life cycle. The arrows also loop back from the "Beyond Life" stage to earlier stages, indicating the potential for recycling and reuse to influence the production of new products.

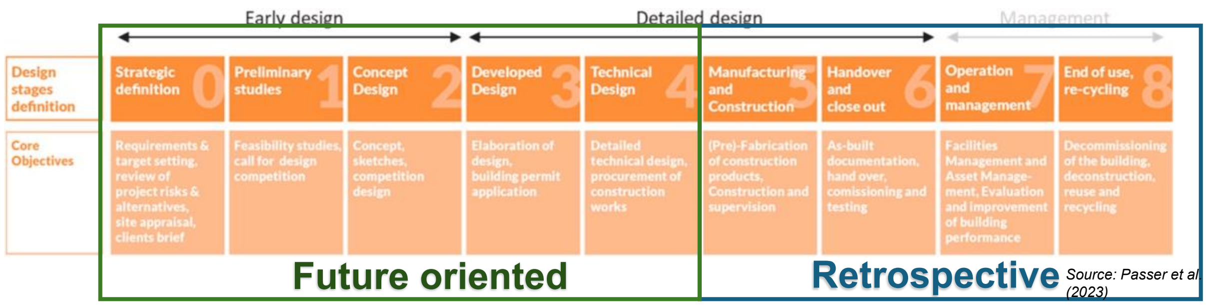
For more details on sustainability see the contents and lecture notes of Lecture 4 (week 4).





Embodied impacts refer to the environmental impacts embedded in the production, construction, and maintenance of infrastructure. This includes energy, carbon emissions, and other resources consumed during these stages. **Operational impacts** refer to the environmental and energy impacts during the use phase of the infrastructure. This typically involves the consumption of electricity, water, and other utilities. **Direct impacts** are the immediate consequences of interruptions on the system itself, such as power outages or system failures. **Indirect impacts** refer to the broader, cascading effects on communities, businesses, and other infrastructures that rely on the uninterrupted functioning of the impacted system.

Sustainability Assessment and integration in planning process - challenges



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®

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This is a summary of the design stages in a project lifecycle, emphasising the importance of early decision-making, particularly in relation to sustainability and Life Cycle Assessment (LCA). Eight distinct stages are included, categorised under "Early Design," "Detailed Design," and "Management":

Strategic Definition (Stage 0): Focuses on setting requirements and targets, reviewing project risks and alternatives, conducting site appraisals, and defining the client's brief. Core Objective: Requirements & target setting.

Preliminary Studies (Stage 1): Involves feasibility studies and calls for design competition. Core Objective: Feasibility studies, call for design competition.

Concept Design (Stage 2): This stage covers concept sketches and competition design. Core Objective: Concept sketches, competition design.

Developed Design (Stage 3): Elaboration of the design, building permit application. Core Objective: Detailed design, procurement of works.

Technical Design (Stage 4): Includes the detailed technical design and procurement of construction works. Core Objective: (Pre)Fabrication of construction products, construction and supervision.

Manufacturing and Construction (Stage 5): Involves the prefabrication of construction products and supervision during construction. Core Objective: Construction of works, completion.

Handover and Close Out (Stage 6): Focuses on documentation, handover, commissioning, and managing operations. Core Objective: As-built documentation, handover, commissioning, management of buildings.

Operation (Stage 7) & End of Life (Stage 8): Operations involve facilities management and performance evaluation. End of life includes decommissioning, reuse, and recycling. Core Objective: Facilities management, building reuse/recycling.

Future-Oriented: The stages from 0 to 4 (Strategic Definition to Technical Design) are labeled as "Future-Oriented," indicating that decisions made during these stages are crucial in shaping the sustainability and overall impact of the project.

Retrospective: Stages 5 to 8 (Manufacturing & Construction to End of Life) are labeled as "Retrospective," highlighting that these phases often involve reflecting on and managing the outcomes of earlier decisions.

LCA as a Decision-Making Tool: the importance of using Life Cycle Assessment (LCA) early in the design process to guide decisions is highlighted. The **improvement potential** is very high during these early stages, while u**ncertainty levels** are also high, making it essential to address and communicate these uncertainties effectively.

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.

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Activity 3. What is Digitalisation?

ACTIVITY 3: What is digitalisation?

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

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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.

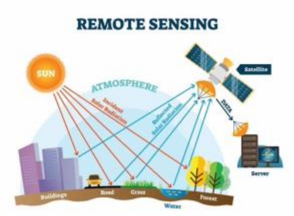
Geographic Information Systems (GIS) combines spatial data with attribute information to create digital maps and models of infrastructure assets. It enables the visualisation, analysis, and management of infrastructure data.

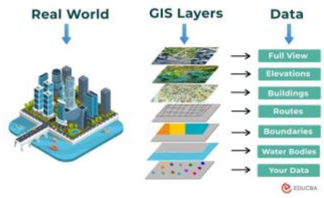
Non-Destructive Testing (NDT) techniques employ digital technologies to assess the condition of infrastructure components without causing damage.

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.





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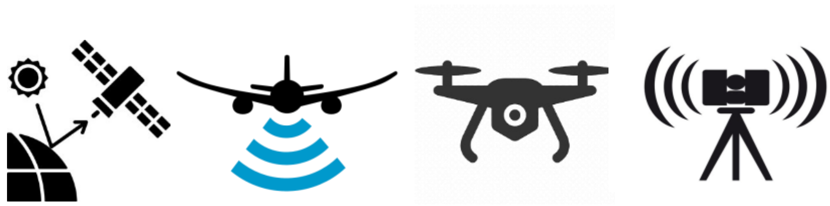
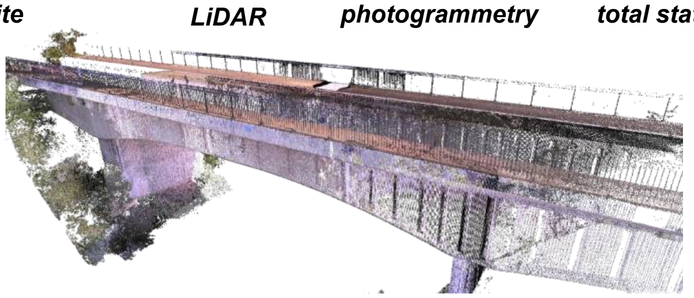
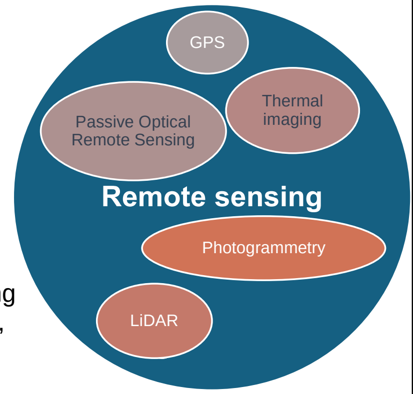
Remote Sensing



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.

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There are several types of digital technologies commonly used for the assessment of infrastructure. These technologies aid in gathering data, analyzing conditions, and providing insights for decision-making. Here are some examples:

Remote Sensing: Remote sensing technologies, such as satellites, aerial photography, and LiDAR (Light Detection and Ranging), provide high-resolution imagery and data about infrastructure assets. These technologies are useful for assessing large-scale projects, monitoring changes, and identifying potential issues.

Geographic Information Systems (GIS): GIS combines spatial data with attribute information to create digital maps and models of infrastructure assets. It enables the visualization, analysis, and management of infrastructure data, aiding in asset inventory, condition assessment, and planning.

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

For more details on digital technologies see the contents and lecture notes of Lecture 5 (week 5).

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

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SHM of infrastructure involves the following tasks:

1. Sensor Deployment: SHM systems are equipped with various types of sensors that are strategically placed on the infrastructure. These sensors can include strain gauges, accelerometers, displacement sensors, temperature sensors, corrosion sensors, and more. The sensors are positioned at critical locations to capture data related to structural responses, environmental conditions, and potential damage indicators.
2. Data Acquisition: The sensors continuously collect data on various parameters, such as stress, strain, vibration, temperature, and environmental conditions. The collected data is transmitted to a centralized data acquisition system for storage and analysis.
3. Data Analysis and Interpretation: The acquired data is processed and analyzed using advanced algorithms and techniques. Data analysis aims to identify patterns, trends, and anomalies in the structural behavior. Changes in stress or strain levels, vibration frequencies, or temperature variations can indicate potential issues or structural degradation.
4. Damage Detection: SHM systems are capable of detecting and localizing damage or defects in the infrastructure. The analysis of the collected data helps identify cracks, deformations, and structural abnormalities that may require attention.
5. Health Assessment and Remaining Life Estimation: SHM enables a continuous assessment of the infrastructure's health. By tracking structural responses over time, engineers can estimate the remaining useful life of the asset and plan maintenance and repair activities accordingly.

6. Real-time Monitoring and Alerts: SHM systems can provide real-time monitoring and alerts for critical events or unusual behavior. When certain thresholds are exceeded or anomalies are detected, alerts are generated to notify engineers and asset managers, enabling timely action.
7. Predictive Maintenance: By continuously monitoring the infrastructure's health, SHM facilitates predictive maintenance strategies. This proactive approach allows maintenance activities to be scheduled when necessary, reducing downtime and extending the life of the asset.
8. Long-term Performance Evaluation: SHM systems help track the long-term performance of the infrastructure, providing valuable data for asset management, performance evaluation, and decision-making related to rehabilitation or replacement.

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

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Markogiannaki et al. (2022)

Digital inspection of structures

Figure 1. Transport and Energy Assets and interdependencies

Figure 2. Digital Technologies

Figure 3. UAV-mapping (drone aerial survey)

Figure 4. The digital twin of the bridge

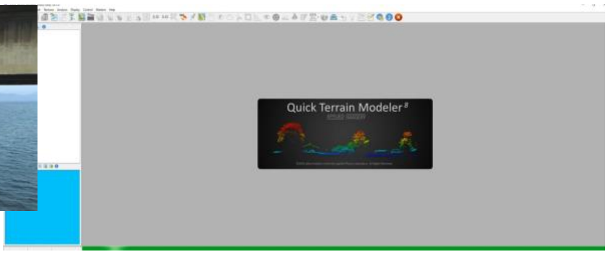


Figure 5. Laser scanner

Figure 6. SAR interferometry (satellite imagery)

The **Lake Polyfytos Bridge** is one of the Recharged project case studies, https://msca-recharged.eu/polyfytos-bridge-greece/ . Is the second longest bridge in Greece, with a length of 1,372 m designed by XEKTE SA and Prof Riccardo Morandi. Construction began in 1972 along with the artificial lake and was completed in 1975. The 45-year-old landmark bridge of the national road network has strong interdependencies with the most important power stations in Southeast Europe.

The risk and resilience of the bridge and adjacent network has been evaluated based on several visual inspections and collection of digital data based (Figures 2-6) on: (a) **digital twin** (Figures 4), which provides a snapshot of the existing geometry of the asset, and a dynamically evolving model that can inform advanced simulations, (b) **satellite imagery** (Figure 6), which provides continuous updates and information about the asset deformations and geometry, and (c) advanced **numerical modelling,** where based on back analysis an interpretation of the current deflections is attempted.

The digital twin of the Lake Polyfytos Bridge was based on state-of the art photogrammetry methods. For the extended survey and the construction of the digital twin more than 1000 high resolution photos were taken per 100m along the length of the bridge, both nadir and oblique in various angles in fully automated missions. Additionally, another 10 ground control points and check points per 100m were defined, for improving the accuracy and consistency of the acquired data. Also, surveying measurements of the structure were taken by making use monitoring-grade total station and **high-precision multi-hour static GNSS measurements** of its' stationary points. All photographs, in raw format, were initially processed through photo-editing software for enhancement and then used in photogrammetry software. The **point cloud** generated has a point-to-point spacing of 7mm and is being used for assessing the current condition and monitor potential evolution of deterioration and structural defects. The most critical structural components of the bridge is currently measured with a **laser scanner.**

Interdependencies with power stations and other critical assets. Figure 1 shows the area of interest with emphasis on the interoperabilities between critical transport and energy assets/infrastructure, and the impact of bridge closure to the connectivity and travel time between major cities in the vicinity of the lake. The four critical assets are the lake Polyfytos bridge, the Rymnio bridge, and two major power stations, the Amyntaio power plant (600MW) and the Polyfytos hydroelectric facility (420GWH per year).

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)

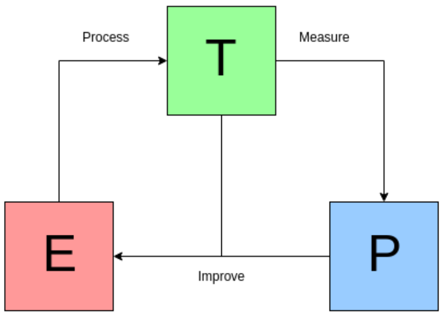
"a computer program is said to learn from

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

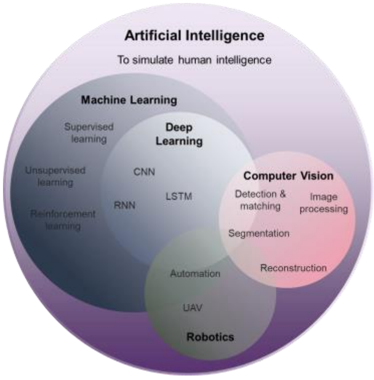
(2) unsupervised learning, and → Unlabelled data

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

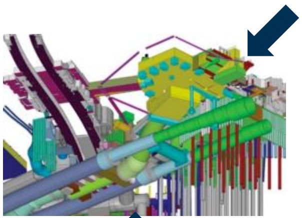
Methods for digital assessment of structures

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

- **Building information Modelling (BIM)**



Non-Graphical Data



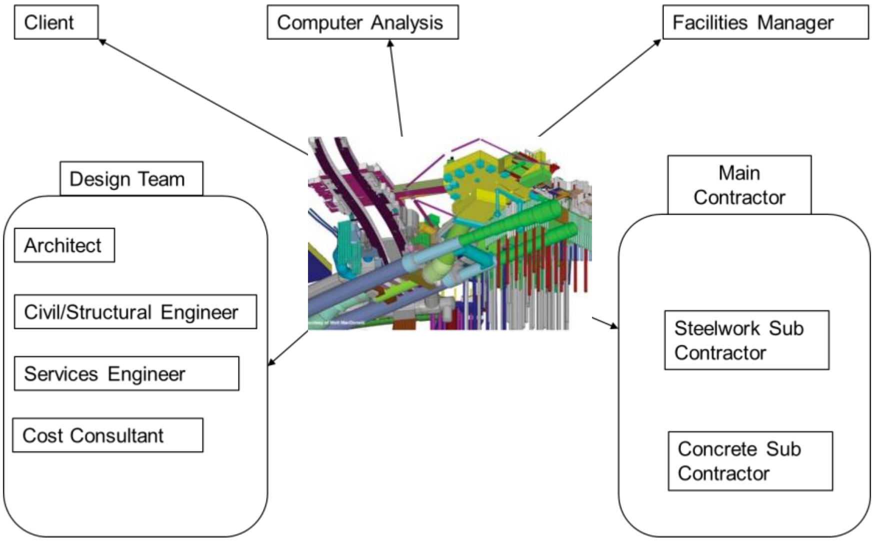
Documents

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™)

Big data and its closely related technologies such as cloud computing, Internet of Things (IoT) and artificial intelligence (AI) have achieved enormous attention in the past decade. AI branches to simulate human intelligence include machine learning, deep learning, computer vision, and robotics “for simulation of” Or “that mimic”

BIM collaborative project development



A BIM model is central to digital construction and involves the generation and management of digital representations of physical and functional characteristics of places. BIM allows for better coordination among stakeholders (architects, engineers, contractors). It enables visualisation of the project before actual construction begins, which aids in detecting potential issues early. BIM improves efficiency by streamlining the planning, design, and construction processes.

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.

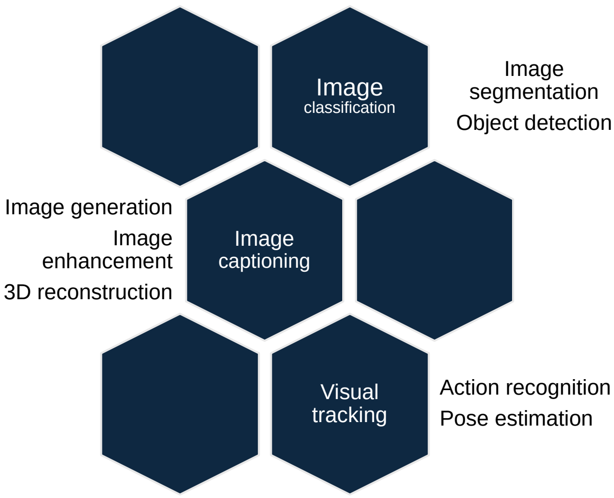
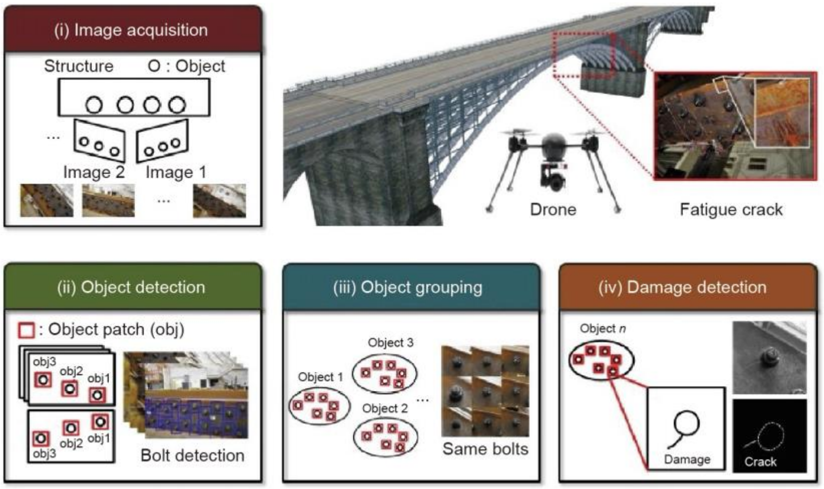


Image analysis with AI is used to automatically categorize and identify various elements in construction images, helping to monitor progress and detect anomalies. AI systems can generate descriptive captions for images, which can be used to automatically document construction progress or identify specific components. AI can track the movement and placement of objects and materials on the construction site in real-time, ensuring that everything is according to the project plan.

Vision based automatic inspection of bridges

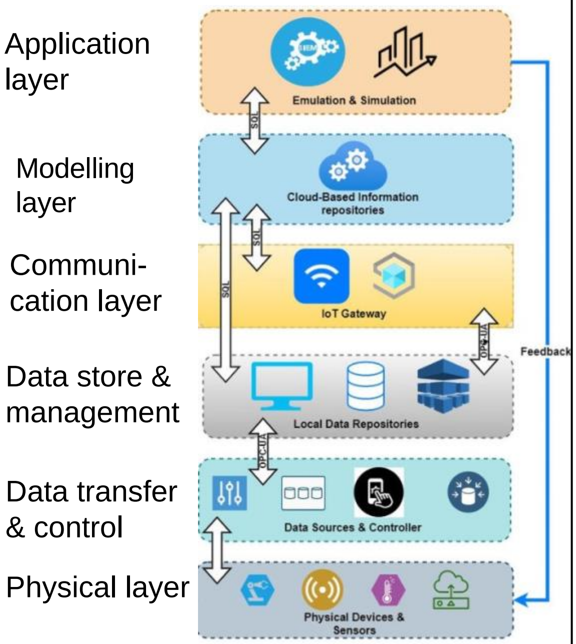
Example of application of Computer Vision methods for inspection and analysis of bridges

- 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



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:

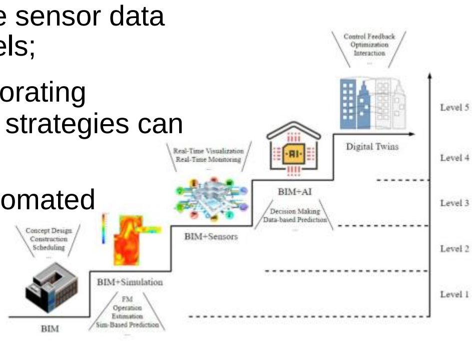


FIG. 1: Evolution of BIM to Digital Twins in the Built Environment

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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)

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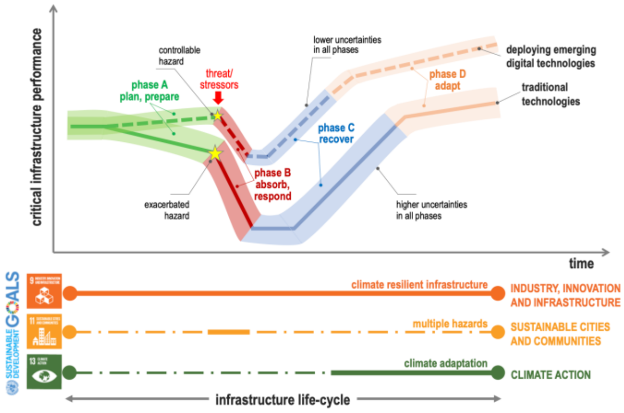
Emerging digital technologies can deliver more efficient, rapid and reliable resilience evaluations and enable better decision-making, based on actionable performance indicators before, during and after the occurrence of hazards. This table shows technology that emerged recently and provides examples of how these technologies can enhance the climate resilience of critical infrastructure. Infrastructure resilience as shown in the figure at the next slide, can be represented through four distinct phases of the infrastructure life-cycle. These phases include planning and preparation before the hazard events, absorption and response during and immediately after the hazard occurrence, followed by recovery and adaptation to novel stressors (Ganin et al., 2016). The same figure shows the benefit of enhanced resilience to SDGs 9, 11 and 13.

Digitalisation in critical infrastructure management

phase of resilience	traditional management ramifications	emerging technologies enhancing different phases of the life-cycle climate resilience: emerging digital technology	5G | internet of things (IoT) | structural health monitoring (SHM)	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		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.

Climate resilience of infrastructure enhanced by emerging digital technologies versus traditional management using conventional approaches. The planning and preparedness (phase A), represent infrastructure performance for normal conditions, during which a gradual loss of operability ensues, e.g. due to ageing effects and asset deterioration. Absorption and response (phase B) are illustrated by the loss of functionality due to hazard events. The recovery (phase C) of the infrastructure functionality, includes the restoration of capacity and reinstatement of the operation. The adaptation (phase D) concerns future stressors, e.g. novel loads, climatically exacerbated hazards, which may take place before or after a hazard event. In all phases, emerging digital technologies significantly reduce aleatory and epistemic uncertainty. SDGs 9, 11, 13, which are underpinned by climate resilience, are represented by the three lines at the bottom of the figure across the infrastructure life-cycle. The continuous segments of these lines correspond to the periods where enhanced resilience influences the SDG directly and to a higher degree. The discontinuous lines refer to the instances where a lower impact is expected (Argyroudis et al., 2022).

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.

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