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

Lecture 4 Sustainability assessment

Lecture Notes

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Introduction

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

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

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

Outcomes

Lecture 4-Week 4
The aim of this week is to provide a detailed understanding of sustainable design principles and life cycle assessment (LCA) techniques, with a specific focus on critical infrastructure projects. The material will delve into concepts of circularity, carbon emissions, relevant databases and assessment tools, and decision-making metrics. By the end of this week, you will be equipped with the knowledge and tools to critically evaluate the carbon footprint of critical infrastructure projects and make informed design decisions.

- Define sustainability in the context of infrastructure projects and explore sustainable design principles in minimizing resource consumption and waste generation.
- Understand the purpose, phases, parameters, and limitations of life-cycle assessments (LCA) in assessing the environmental impact of products and projects.
- Undertake whole-life carbon emissions assessments for infrastructure assets and networks, and adopt low-carbon solutions, and use sustainability metrics for decision-making on practical case studies.

Lecture 4. Sustainability assessment

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In this lecture, we will define sustainability, particularly within the context of infrastructure projects, and explore sustainable design principles aimed at reducing resource consumption and waste generation. We will examine the purpose, phases, parameters, and limitations of life-cycle assessments (LCA) as a tool for evaluating the environmental impacts of products and projects. Additionally, we will conduct whole-life carbon emissions assessments for infrastructure assets and networks, explore low-carbon solutions, and apply sustainability metrics in practical case studies to guide decision-making.

Activity 1. Introduction to sustainability and circularity

In this activity, sustainability within the context of infrastructure projects will first be defined. Then, the importance of sustainable design principles will be explored, focusing on how they help minimise resource consumption and waste generation. Finally, the role of circularity in enhancing the sustainability of infrastructure projects will be discussed.

Planetary boundaries define the safe operating space for humanity, standing for the limits within which human activities should remain to avoid destabilising the system of the planet: climate change, change in biosphere integrity, modification of biogeochemical flows, introduction of novel entities, land system change, freshwater change, stratospheric ozone depletion, ocean acidification, and increase in atmospheric aerosol loading. Unfortunately, humanity has crossed several of these boundaries, including climate change, biodiversity loss, and biogeochemical flows, threatening the stability and resilience of the life-support systems of our planet (Richardson et al. 2023; Steffen et al. 2015; Rockström et al. 2009).

The built environment is responsible for 8 % of global CO2 emissions from cement production and expected to grow by 12-23% by 2050. Additionally, 50% of the world steel production is used in construction (25% structural steel, 44% - reinforcement, 31% other elements) generating between 3.5 and 4.5% of direct emissions from the global use of fossil fuel (Andrew, 2018; IEA, 2018). The steel requirements are expected to grow by at between 1.4-4% globally, reaching around 2.0 billion tonnes by 2035 (van Audenaerde, 2017).

What is sustainability?

Sustainability has evolved significantly over time, rooted in early environmental awareness and gaining momentum through global recognition of the need for responsible resource management. The roots of sustainability can be traced back to ancient practices of resource management, such as the concept of sustainable yield in forestry, where the amount of wood harvested was balanced with the amount regrown. In the 18th and 19th centuries, concerns about deforestation and resource depletion led to the first formal conservation movements, particularly in Europe and North America.

The Industrial Revolution in the 19th century brought rapid industrialisation and urbanisation, leading to significant environmental degradation. This period marked the beginning of widespread pollution, habitat destruction, and resource depletion. However, it also spurred the development of early environmental thinking, with figures like John Muir advocating for the preservation of wilderness. The aftermath of World War II saw unprecedented economic growth, but also environmental harm. The Silent Spring by Carson (1962) highlighted the dangers of pesticides and sparking the modern environmental movement. This period also saw the establishment of major environmental protection laws and the creation of organisations like the United Nations Environment Programme (UNEP) in 1972.

In 1987, the Brundtland Report, officially titled Our Common Future, was published by the World Commission on Environment and Development (Brundtland Commission, 1987). It introduced the concept of sustainable development, defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. This report significantly influenced global environmental policy and set the stage for later international efforts. The 1992 Earth

Summit in Rio de Janeiro further advanced the sustainability agenda, leading to the adoption of Agenda 21, a comprehensive plan for sustainable development (UN, 1992). The Kyoto Protocol (1997) and the Paris Agreement (2015) followed, focusing on combating climate change by reducing greenhouse gas emissions (UNFCCC, 1997; UN, 2015)

In the 21st century, sustainability has become a central concern for governments, businesses, and civil society. The United Nations' Sustainable Development Goals (SDGs), adopted in 2015, provide a global framework for achieving sustainability by 2030. The concept encompasses not only environmental stewardship but also social equity and economic viability, reflecting the interconnectedness of these domains in keeping a healthy planet. This history reflects the growing recognition of the need to balance human development with environmental preservation, ensuring that future generations inherit a planet capable of sustaining life.

The concept of the Triple Bottom Line (TBL) shown in Figure 1 was first introduced 90's (Elkington and Rowlands, 1999). The TBL framework challenged businesses to measure their success not just by financial performance but also by their social and environmental impact.

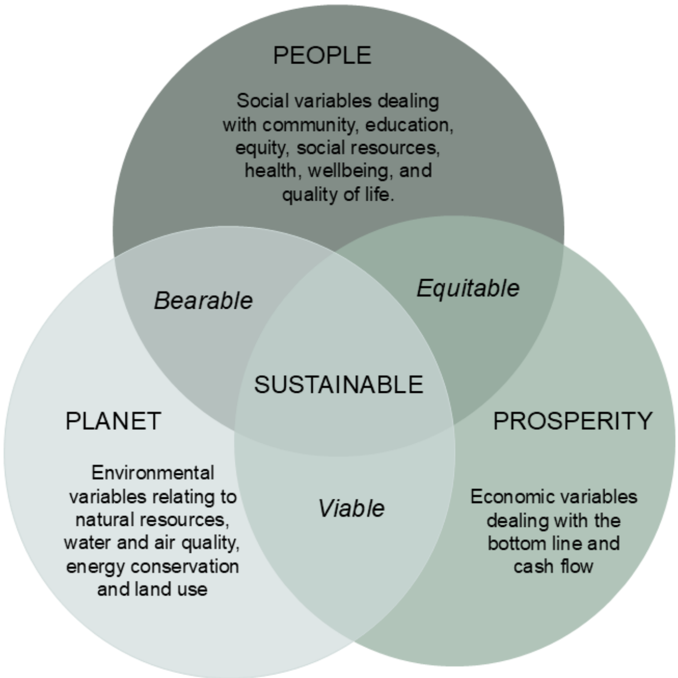


Figure 1 The triple bottom line.

The triple bottom line (TBL) framework encourages companies to expand their traditional focus on profit to also include social and environmental concerns, thereby creating a more integrated approach to business success. According to the TBL theory, businesses should measure their performance based on three interconnected bottom lines: profit, people, and the planet. Profit refers to the financial aspect, ensuring that the company stays economically viable. People emphasise social responsibility, where businesses are expected to positively influence their employees, customers, and the broader community. The planet dimension highlights the importance of environmental stewardship, urging companies to minimise their ecological footprint by adopting sustainable practices.

This framework moves beyond the narrow focus on financial gain, advocating for a balance between economic growth, social equity, and environmental protection. By integrating these three pillars into their operations and decision-making processes, businesses can contribute to long-term sustainability. TBL challenges the conventional notion that profit is the sole indicator of success, instead promoting a more inclusive approach that recognises the interconnectedness of economic, social, and environmental factors. As such, companies adopting the TBL framework not only aim for profitability but also strive to create positive social impacts and preserve the environment for future generations.

The concept of 'weak' versus 'strong' sustainability pertains to differing views on how human activities should balance economic development and environmental protection (Pearce et al., 2006) (Figure 2).

Weak sustainability allows for the substitution of natural capital with human-made capital. It suggests that as long as the overall stock of capital (natural plus human-made) remains constant or increases, economic growth can continue, even if natural resources are depleted or degraded (Neumayer, 2003). *Strong sustainability*, on the other hand, emphasises that natural capital should not be substituted by human-made capital. It posits that certain natural resources and ecological processes are irreplaceable and must be preserved for future generations, regardless of the potential for technological or economic advancements (Daly and Farley, 2011).

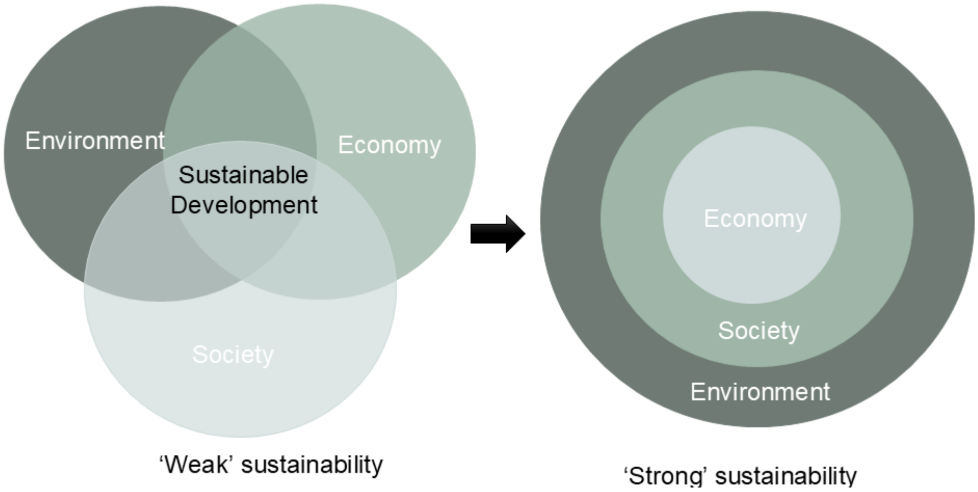


Figure 2 Weak and strong sustainability models.

Socio-ecosystemic sustainability, rooted in the principles of strong sustainability, has evolved over the past 50 years, beginning with the Brundtland Report and progressing through the Millennium Development Goals (2000-2015) to the UN Sustainable Development Goals (SDGs) of 2015. This adaptive process recognises that goals focused solely on economic growth are incompatible with the natural processes of the biosphere.

The concept of the quadruple bottom line shown in Figure 3 expands upon the traditional three pillars of sustainability—economic viability, environmental protection, and social equity—by adding a fourth dimension: cultural impacts. This added dimension stresses the importance of integrating cultural considerations into sustainable design. It highlights the need to respect and incorporate cultural values, heritage, and identity into projects, ensuring that cultural impacts are explicitly addressed and considered (Schultz and Fisher, 2013).

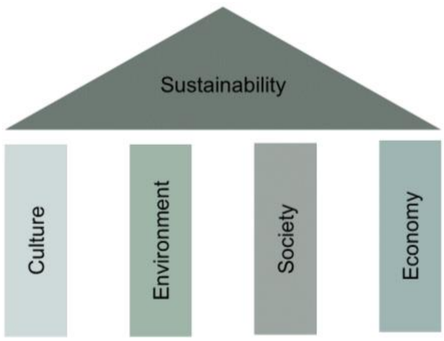


Figure 3 Quadruple bottom line.

Following the evolution from the triple to the quadruple bottom line, the Sustainable Development Goals (SDGs) serve as a comprehensive blueprint for creating a more equitable and sustainable future. The SDGs address a broad spectrum of global challenges, including poverty, inequality, climate change, environmental degradation, and the pursuit of prosperity, peace, and justice. Encompassing 17 goals with approximately 170 specific targets to be achieved by 2030, the SDGs offer a universal framework essential for all sustainable designers, regardless of their domain. The first 12 SDGs focus on distinct categories, such as clean water, affordable energy, and quality education. Goals 13 through 17 build

upon these by integrating broader, systemic aspects like climate action, responsible consumption, and partnerships for the goals.
Building on the quadruple bottom line and describing in more detail the UN Sustainable Development Goals, PYXERA Global (2015) provides insights and frameworks for understanding and implementing the United Nations Sustainable Development Goals (SDGs) (see Figure 4). They focused on translating these goals into actionable strategies for businesses, non-profits, and governments, aiming to foster sustainable development through partnerships and collaborative efforts.

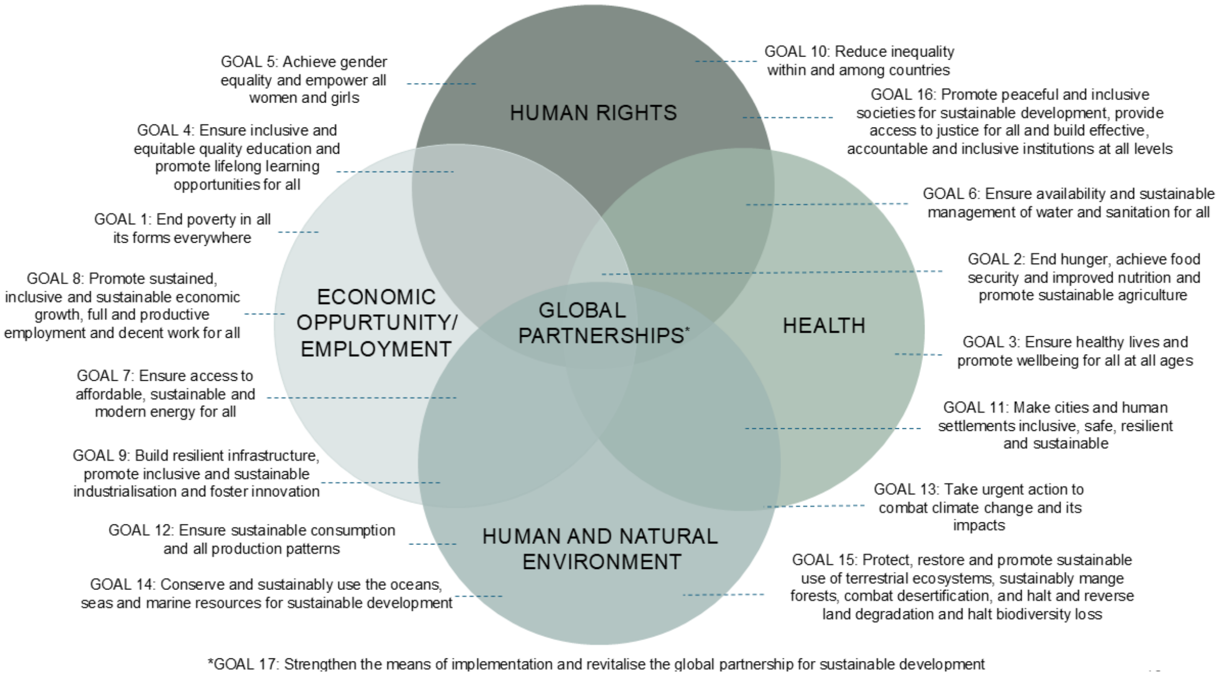


Figure 4 UN Sustainable Development Goals mapped (adapted from PYXERA Global, 2015).

Sustainable design

Sustainable design is an approach to creating buildings, infrastructure, and products that aim to minimise environmental impact, promote resource efficiency, and enhance the well-being of occupants and users. It incorporates principles such as energy efficiency, the use of renewable resources, reduction of waste and emissions, and the conservation of natural habitats (Lehmann, 2010). Sustainable design also considers the entire life cycle of a project, from materials sourcing and construction to operation, maintenance, and eventual decommissioning or reuse, to reduce the overall carbon footprint and contribute to long-term ecological balance (Curran, 2012). This approach is critical in transforming cities and structures to be more sustainable, as outlined in works such as Bergman (2012) and Schwartz (2015). Green building practices, such as those detailed by Kruger and Seville (2013), further emphasise the importance of integrating sustainability into residential construction, underscoring the broad applicability of sustainable design principles across different sectors.
Sustainable design is an overall umbrella, however, there are several basic levels of design related to sustainability (Figure 5).

- *Green Design*. Involves replacing basic components with environmentally friendly alternatives, such as using recycled plastic (e.g., tyre fibres) instead of conventional plastics (McDonough and Braungart 2002).
- *Eco-Design*. Goes beyond individual materials by focusing on the life cycle assessment (LCA) of products. This approach evaluates impacts through various stages: extraction, production, consumer use, and disposal, considering both upstream and downstream effects. However, eco-design often overlooks social impacts and fairness (Fiksel, 2009).
- *Sustainable Product Design*. Minimise negative impacts through product's life cycle by selecting eco-friendly materials, optimising processes, enhancing durability, and ensuring responsible end-

of-life management, while also addressing broader societal impacts and fairness (Manzini and Vezzoli, 2003).

- *Design for Sustainability*. Incorporates societal impacts and broader strategies, including democracy and justice (Gibbs, 2009).
- *Transformative Design*. Builds on all the above aspects and integrates considerations of human experience and future implications (Brown, 2009).

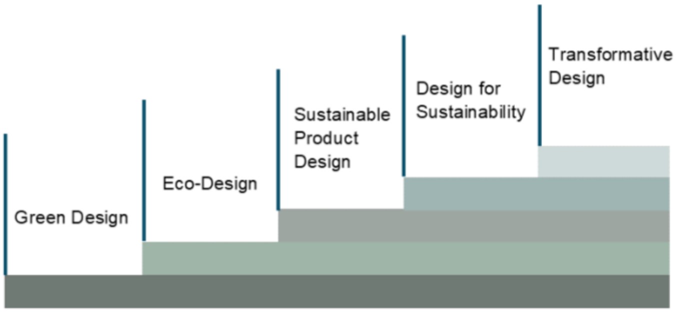


Figure 5 Basic levels of design.

Following up on the product design, the terms described below are stages or levels of sustainability practices and philosophies (Mang and Haggard, 2016), reflecting the evolution from minimal environmental concern to more proactive and restorative approaches (Figure 6).

- *Business as Usual*. This approach maintains conventional practices without significant changes, often prioritising short-term economic gains over long-term environmental or social impacts. It typically involves standard industry practices with minimal consideration for sustainability.
- *Green*. Green practices focus on reducing environmental harm by incorporating eco-friendly materials or technologies, such as using recycled plastics. While these practices aim to lessen negative impacts, they often do not address broader systemic issues or the full lifecycle of products.
- *Sustainable*. Sustainable practices go beyond green approaches by aiming to balance environmental, social, and economic factors. They look to minimise negative impacts throughout the lifecycle of a product and promote practices that do not compromise future generations' ability to meet their needs.
- *Restorative*. Restorative approaches aim to repair or regenerate ecosystems and communities affected by industrial activities. This involves not only reducing harm but also actively restoring and enhancing environmental and social conditions, such as through habitat restoration projects or social equity initiatives.
- *Regenerative*. Regenerative practices aim to create systems that restore, renew, and enhance their environment and society beyond their original state. This approach looks to build resilience and vitality by creating positive impacts that contribute to the health and regeneration of ecological and social systems, fostering overall sustainability and flourishing.

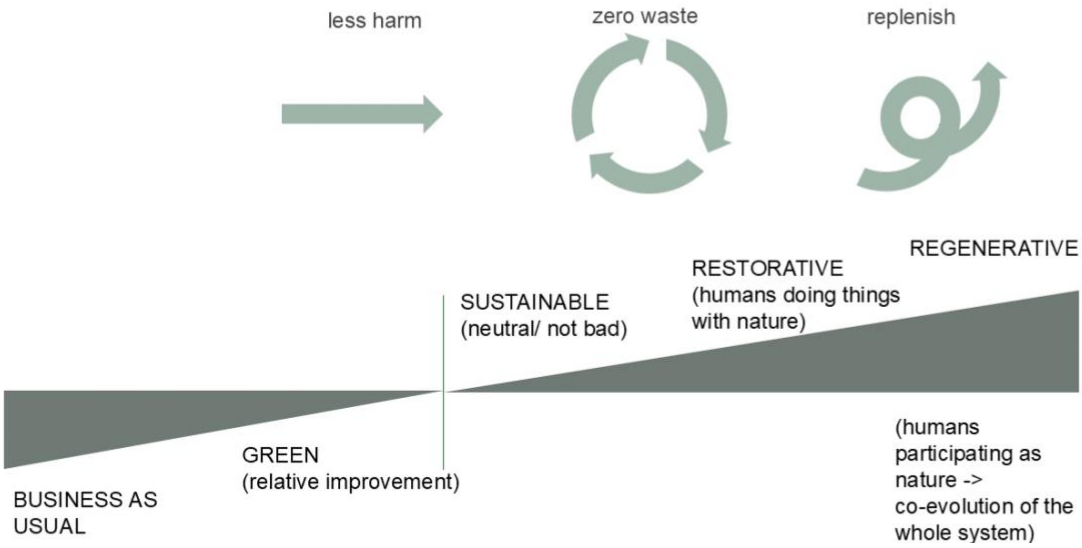


Figure 6 Sustainability practices and philosophies.

Circularity fundamentals

Modern society excels at creating highly efficient linear production lines, characterised by a 'take-make-waste' process (Benyus, 1997). These linear systems involve the extraction of raw materials, production, consumer use, and disposal, resulting in significant waste during the end-of-life phase (Figure 7a). Such systems rapidly deplete natural resources and convert them into waste, highlighting the unsustainable nature of linear production. This raises critical questions about the environmental costs of activities and highlights the need to challenge prevailing worldviews and paradigms.

Currently, the current practice of constructing environmentally friendly built environment is based on the pursuit of short-term measurable performance objectives, which ensures the certainty of outcomes. For example, this is the case of various building tools for measuring the environmental performance of buildings (LEED, BREAM), or largely the case of PAS 2080:2023, which aims to provide a common process for the built environment value chain on how to manage whole life carbon in projects and programmes of work. Whilst there is acknowledgment of circular principles, the approach focuses on whole-life carbon. This gives guidance on how to maximise whole-life carbon reductions at all stages of the project delivery process, select appropriate carbon emissions assessment methodologies, set appropriate carbon reduction targets, determine baselines against which to assess carbon reductions, establish metrics (e.g. key performance indicators) for credible carbon emissions monitoring and reporting, integrate carbon management into procurement; and continual improvement of carbon management and performance (PAS2080:2023).

A circular economy is defined as an economic system that adopts a systemic approach to eliminate waste and optimise resource utilisation (Figure 7b). The primary goal is to redefine growth for sustainable development across businesses, society, and the environment, closing the gap between production and the lifecycle of ecosystems (Modibbo et al., 2023). The concept of Circular Economy is gaining significant attention as an essential shift from the linear economy, emphasising sustainability goals. In contrast to the linear economy, the developed method goes beyond user requirements to consider the actual end users and end-of-life process chains during product design. This approach anticipates a circular flow of resources by integrating considerations beyond the initial use of the asset (Mangers et al., 2023). The focus is on end-of-life decision-making for infrastructure assets and buildings, to support the shift towards a circular economy in the construction sector (Nik-Bakht et al., 2023).

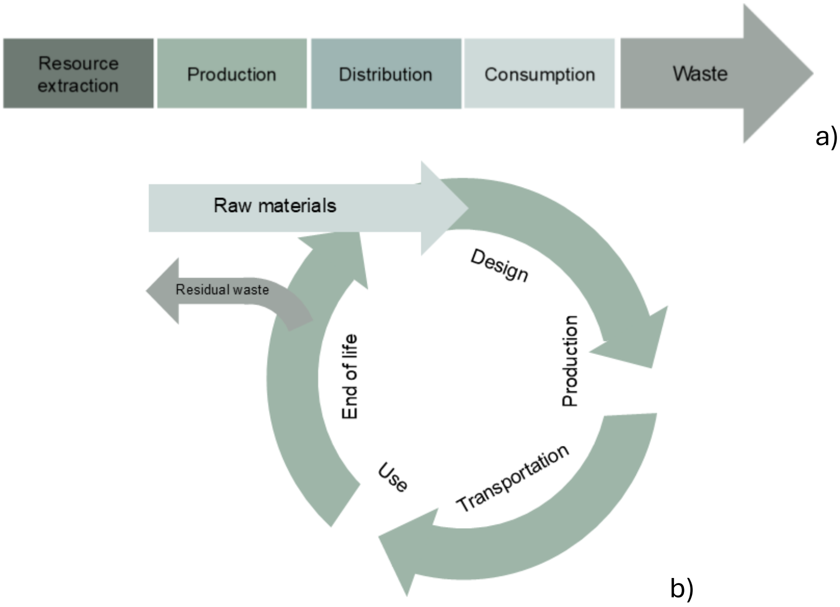


Figure 7 a) Linear economy model, b) Circular economy model.

Circular Economy (CE) can be achieved through four resource strategies: narrowing, slowing, closing, and regenerating the loop (Çetin et al., 2021). Narrowing resource flows refers to using fewer resources throughout the lifetime of an infrastructure asset and includes approaches such as minimising the primary resource inputs, improved efficiency or lean design. The principle of slowing resource loops aims to decelerate the pace of resource flows by enhancing their use and prolonging their valuable lifespan through the implementation of design and operational strategies. This refers to design for durability, long life and life extension, for adaptability and reversibility, reuse and repurpose. The objective of the closing resource loops principle is to reintegrate resources into the economic cycle after assets reach their end-of-use stage and include principles such as harvesting or urban mining (e.g. structural components), as well as recycling and incorporating into new materials or elements (e.g. recycled aggregates from demolition waste, or scrap steel into new profiles). Regeneration goes beyond the physical and material aspect, and addresses issues on a wider scale, with a net-positive impact on climate, biodiversity, and the well-being of communities.

The butterfly diagram from Figure 8provides a visual representation of the circular economy by illustrating the flow of materials and resources through two distinct cycles (Ellen MacArthur Foundation, 2019). The biological cycle, which focuses on regenerative processes (such as bamboo and timber), and the technical cycle, which emphasises the maintenance and enhancement of materials, including, in the context of construction, concrete, metals, plastics, etc. There are two fundamental concepts to highlight within the figure: leakage out of the circular system, to energy recovery or landfill, should be avoided wherever possible; within the concentric circles, the smaller the diameter the more efficient the process. The Ellen MacArthur figure is in fact conceptually, similar to the EU and UK waste hierarchy which ranks waste management options according to what is best for the environment and has been a central concept in EU and UK waste policy frameworks for many years.

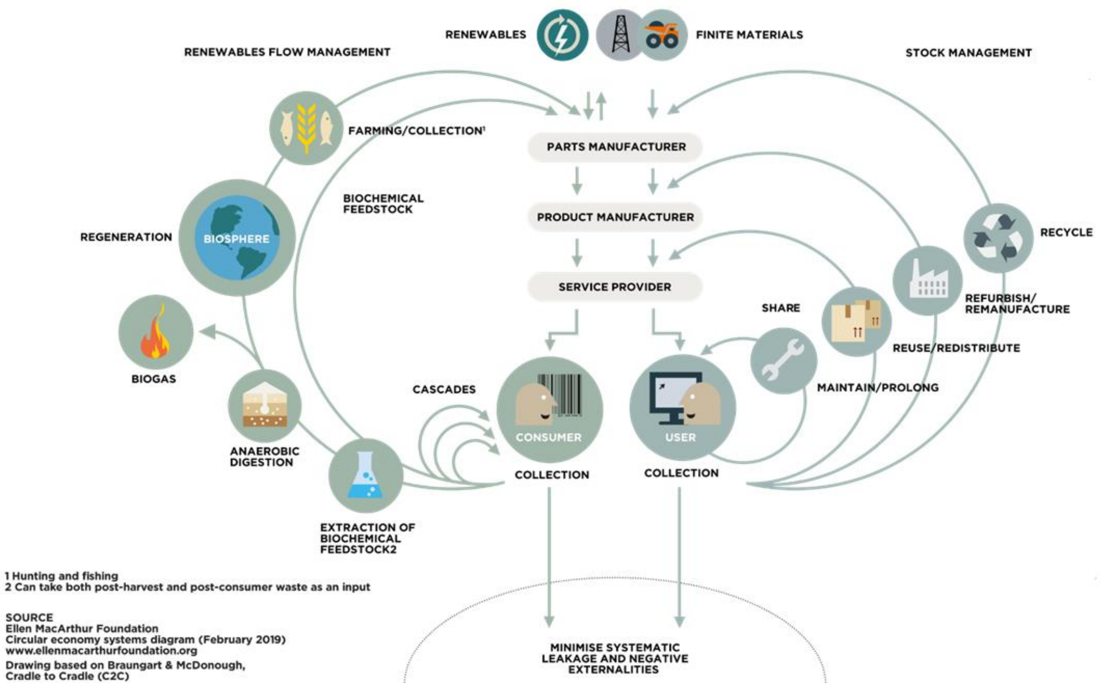


Figure 8 Circular economy systems diagram (adapted from Ellen McArthur Foundation Butterfly Diagram, 2019)

The biological cycle focuses on materials that can safely return to the environment, promoting regenerative processes. Products designed for this cycle are made from biodegradable materials that decompose naturally, contributing to soil health and enhancing ecosystems. This cycle aims to close the loop in nature by using organic inputs that support the regeneration of natural systems. The technical cycle involves materials and products that are designed to be durable, reusable, and easily disassembled. This cycle emphasises the optimisation of resource use by maintaining the value of products, components, and materials through continuous reuse, refurbishment, and recycling. It aims to keep technical resources in use for as long as possible, reducing waste and promoting resource efficiency.

In the built environment, the biological cycle focuses on integrating regenerative and biodegradable materials into construction and design. This approach involves using materials that can decompose naturally and enrich the ecosystem once their useful life is over. Employing materials such as bamboo, cork, or certain types of hempcrete that naturally decompose and integrate back into the environment. Designing buildings that support environmental regeneration, such as incorporating green roofs and walls that promote biodiversity, enhance air quality, and manage stormwater effectively, also aligns with the biological cycle.

The technical cycle in the built environment focuses on designing buildings and infrastructure that maximise material longevity and facilitate easy disassembly and reuse (Crawford, 2011). For example, designing buildings with high-quality, durable materials that extend their lifespan and reduce the need for frequent replacements. This includes using materials like high-performance concrete and modular components that are resistant to wear and tear. Additionally, incorporating design strategies that allow for easy disassembly and reuse of building components is also an alternative. Finally, establishing systems for the recovery and recycling of building materials at the end of their life cycle is essential.

Circularity approaches

Within the context of the circular economy, it is essential to differentiate between reuse and recycling, as their definitions vary. Recycling involves converting waste materials into new materials or products, which may or may not resemble the original form, and generally requires energy. In contrast, reuse refers to using an object in its original form after its initial use, with only minor alterations, thus preserving its original shape and functionality. This distinction is significant, particularly given that the term ‘recycling’ often has a broad, imprecise definition in everyday language, while it holds a more specific meaning within waste management and circular economy frameworks, as outlined by the EU and UK waste management hierarchy (Figure 9).

Sustainability and circularity need to be integrated at all stages of a project. When it comes to sustainability and circularity enhancements, the ways to improve depends on the project type its stage. The earlier the discussions, the higher the influence on carbon reductions, or on project circularity. For example, at the Need/Strategy stage, the site selection, retrofit/retain, or adaptive reuse (in the buildings' context) are a few options. When going deeper into the project, at the optioneering stage (concept design) carbon savings can be achieved through an adequate material selection, selection of the structural system, as well as meeting targets, benchmarking and holistic design. Finally, as the project is at the Design/Technical design stages, savings typically can be achieved through material specification and/or section/structure optimisation.

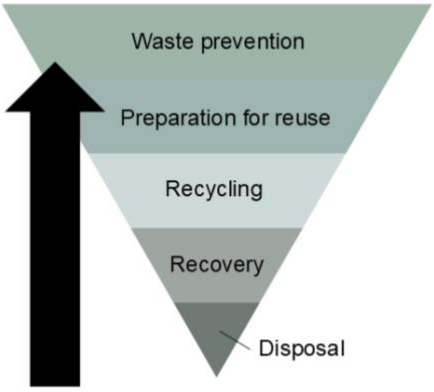


Figure 9 Waste hierarchy.

At an early stage of the design process, aligning with the EU/UK waste hierarchy, the stakeholder group can adopt the most efficient strategy (Figure 10). This can include

- *Retain and retrofit.* Most of the asset fabric is retained, with the asset refurbished for the same or new uses through restoring, refinishing and futureproofing. This also encompasses retrofitting, where new technology or features are added to the existing assets to make them more efficient and to reduce their environmental impacts (e.g. new pavement that has less impact on fuel consumption).
- *Partial retention and refurbishment.* Significant quantities of carbon-heavy aspects of the asset are retained in place, such as the floors and substructure, with the replacement of some elements of the asset. More significant refurbishment can involve adding, for example, extra lanes for traffic on a bridge.
- *Disassemble and reuse.* Disassemble sections of an asset and enable their direct reuse ideally on the site or, where this is not possible, off-site (with nearby sites preferred). This approach also includes careful selective deconstruction of the asset and material types i.e. taking apart each layer and material type as much as possible, minimising damage to parts and maintaining their value, and then reusing those elements and materials. If reuse is not possible, materials may be carefully and selectively separated for processing and recycling into new elements, materials and objects.
- *Demolish and recycle.* Conventional demolition, with elements and materials processed into new elements, materials and objects for use on the site or another site.

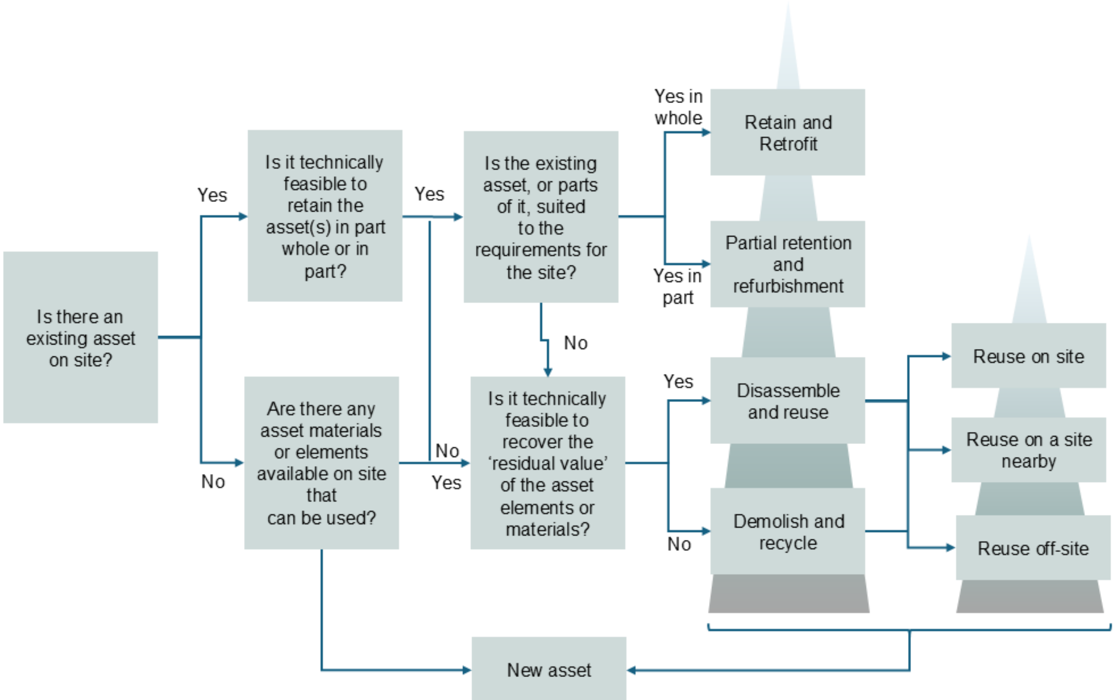


Figure 10 Decision tree for design approaches for existing assets (Modified from London Plan Guidance – Circular Economy Statements, 2022)

All developments should be designed so that assets can be adapted to extend their life (Figure 11). They should also be designed so they can be deconstructed and reconstructed to allow components and materials to be salvaged for reuse or recycling, whilst maintaining their economic and environmental value. Some strategies are:

- *Asset relocation*. Designing to allow the whole asset to be used on a different site, either by moving it as a whole or disassembling it into large modules.
- *Component or material reuse*. The use of a product in its original form with minimal reprocessing. Preparation for reuse involves checking, cleaning or repairing materials so that they can be used again for their original purpose. Materials can be reused as a whole; redeployed as modules; or reused as a kit of parts on one or more different sites.
- *Flexibility*. An asset that has been designed to allow for a change in functional purpose (e.g. 2 to 3-lane traffic; from 3-lane car to mixed-use car, cycle, pedestrian, etc.)
- *Replaceability*. Designed to facilitate easy removal and upgrade, and ideally to be reused, remanufactured or recycled on a part-by-part basis.
- *Disassembly*. Designed to allow the asset and its components to be taken apart with minimal damage to facilitate reuse or recycling. If designed well, it should be possible to replace any component.
- *Longevity*. Designing to avoid a premature end of life for all components through considering maintenance and durability.
- *Adaptability*. A building that has been designed with the thought of how it might be easily altered to prolong its life, for instance by alteration, addition, or contraction, to suit new uses or patterns of use (often used interchangeably with flexibility; however, it relates more to structural changes).

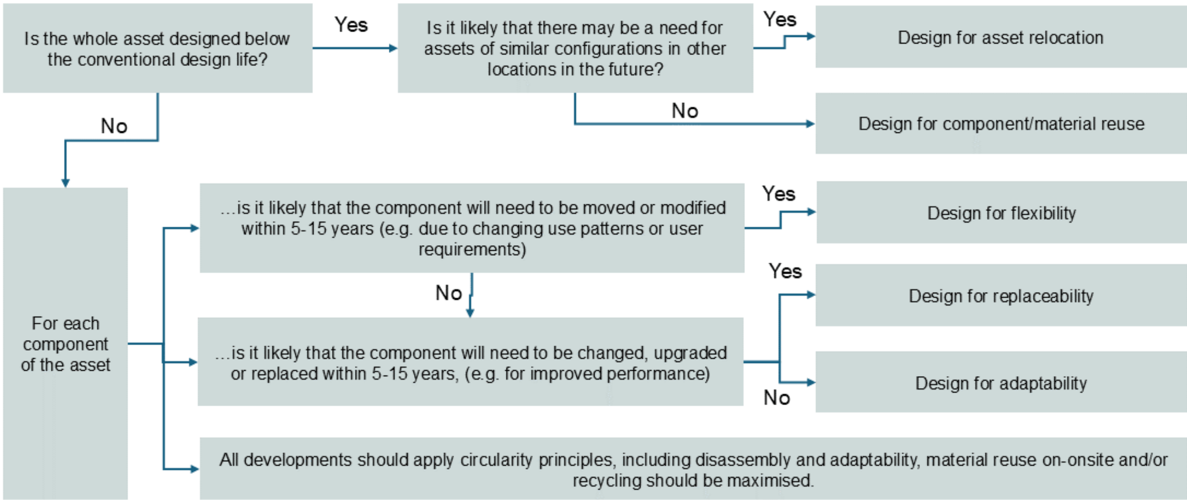


Figure 11 Design tree for design approaches for new assets (Modified from London Plan Guidance – Circular Economy Statements, 2022)

Summary

In this activity, sustainability within the context of infrastructure projects was first defined. Then, the importance of sustainable design principles was explored, focusing on how they help minimise resource consumption and waste generation. Finally, the role of circularity in infrastructure development was covered. Sustainability has evolved from early environmental awareness to a comprehensive framework encompassing environmental, social, and economic considerations. The Brundtland Report (1987) introduced "sustainable development," advocating for meeting current needs without compromising future generations. The Triple Bottom Line (TBL) concept expanded sustainability to include profit, people, and the planet, while the Quadruple Bottom Line added cultural impacts. The UN Sustainable Development Goals (SDGs) further refine this approach, providing a global framework for sustainable development by 2030.

Sustainable design focuses on minimising environmental impact, enhancing resource efficiency, and promoting occupant well-being throughout the entire life cycle of buildings and products. It includes various approaches, such as green design, which substitutes eco-friendly materials; eco-design, which evaluates life cycle impacts; and transformative design, which integrates human experience and future implications. Sustainable practices evolve from basic green initiatives to restorative and regenerative approaches that aim to repair and enhance ecosystems. The circular economy, central to sustainable design, contrasts with linear production by emphasising resource reuse, recycling, and regeneration, thus promoting long-term ecological balance and reducing waste.

Activity 2 Life-cycle assessments

Life Cycle Assessment (LCA) is recognised as an essential methodology for evaluating the environmental impacts of products and projects throughout their entire life cycle. In this section, the definition and purpose of LCA are introduced, with an emphasis on its importance in sustainable decision-making. The key stages of LCA, including goal and scope definition, inventory analysis, impact assessment, and interpretation, are explored. Additionally, an overview of various LCA software and tools available is provided to aid in streamlining and enhancing the accuracy of environmental assessments.

Life cycle assessment

The Life Cycle Assessment (LCA), as defined by ISO 14040:2006 'Environmental management. Life cycle assessment. Principles and framework' (in the UK, BS EN ISO 14040:2006+A1:2020), is the 'compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle.' The LCA addresses only environmental considerations, while economic, social, and other aspects may require additional tools. It is an iterative process, where each phase builds on the results of the others.

The LCA process is split into life cycle stages (modules) and LCA phases (steps) as shown in Figure 12. The stages (modules) are portions of the product life cycle and phases (steps) are the portions of the LCA process. The data is collected on the inputs and outputs of the system, focusing on their associated environmental and resource impacts. It means that through LCA there is a detailed quantification of all resources (inputs) and emissions or waste (outputs) associated with each stage of life cycle of a product—from raw material extraction through production, use, and disposal. Then, the approach evaluates how these quantified inputs and outputs affect the environment, such as contributions to global warming, resource depletion, pollution, and other environmental concerns.

In Life Cycle Assessment (LCA), phases (steps) and stages (modules) play distinct roles. Phases represent the procedural steps within the LCA methodology. These include the Goal and Scope Definition phase, where the purpose of the LCA is established, along with the system boundaries and the level of detail required. The Inventory Analysis (LCI) phase involves collecting data on the inputs (e.g., energy, materials) and outputs (e.g., emissions, waste) associated with each stage of the life cycle. The Impact Assessment (LCIA) phase focuses on evaluating the potential environmental impacts linked to the inputs and outputs identified in the inventory analysis, such as global warming potential, acidification, and resource depletion. Finally, the Interpretation phase involves analysing the results to draw conclusions, make recommendations, and ensure consistency with the goals defined in the initial phase.

Stages refer to the different segments of a life cycle. These typically include several key stages: Raw Material Extraction, where raw materials are acquired from the environment; Manufacturing, which involves converting these raw materials into finished products; Distribution, covering the transportation and logistics required to deliver the product to the user; Use, representing the period when the product is actively utilised by the consumer; and End-of-Life, the final stage where the product is disposed of, recycled, or otherwise processed after its useful life has ended. The key difference between phases (steps) and stages (modules) lies in their focus. Phases focus on the analytical steps of the LCA process, which assess and interpret the environmental impacts across the stages of the life cycle. In contrast, stages pertain to the physical progression of the product from creation to disposal.

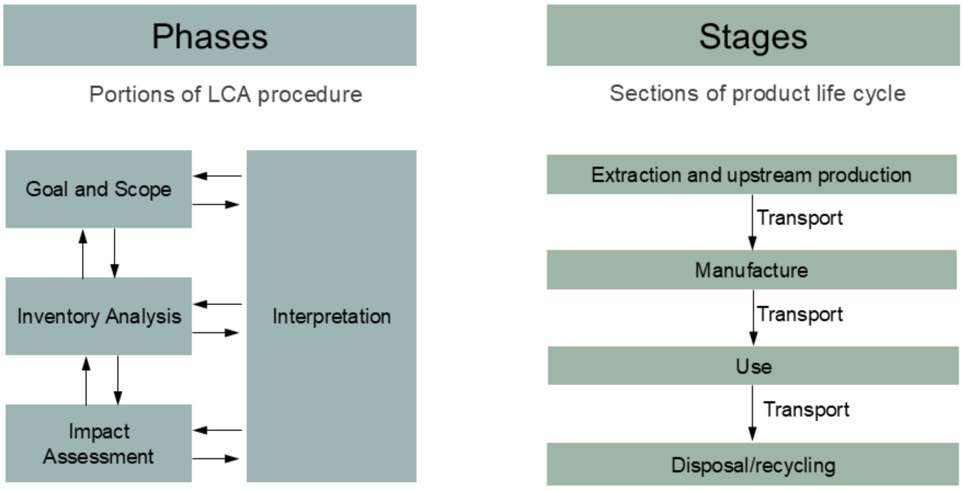


Figure 12 Phases versus stages in LCA per ISO 14040

When undertaking an LCA as per ISO14040 one needs to answer the following questions:

- What do we want to know? (goal, attributional/consequential)
- What is the product/service (in quantitative terms)? (scope, functional unit)
- Inventory. What emissions to and resources from the environment are needed? (life-cycle inventory)
- How do these processes affect the environment? (impact assessment)

In the context of Life Cycle Assessment (LCA), as outlined in ISO 14040, the distinction between ‘attributional’ and ‘consequential’ approaches pertains to the scope and focus of the assessment. Attributional LCA aims to quantify the environmental impacts associated with a product or service based on its entire life cycle, considering the inputs and outputs directly associated with it. This approach typically looks to allocate the environmental burdens to the product or service in question, reflecting the current state of the system and its existing practices. Attributional LCA might calculate the total emissions related to the production and use of a specific type of building material. Consequential LCA, on the other hand, focuses on the changes that result from decisions or actions, including potential shifts in production or consumption patterns.

The functional unit is a critical part of the Life Cycle Assessment (LCA) that specifies the quantifiable measure of the function or service provided by a product or system. It sets up a consistent basis for comparison by defining the amount of service or performance delivered, such as ‘thermal insulation of 1 square metre of wall for 50 years.’ This allows for fair and relevant evaluation of various products or systems, ensuring that environmental impacts are assessed relative to the same functional output. By clearly defining the functional unit, LCA ensures that results are meaningful and applicable for decision-making, facilitating effective comparison and analysis.

In ISO 14040, the Life-Cycle Inventory (LCI) phase involves the systematic collection and analysis of data about the inputs and outputs associated with a product or system throughout its life cycle. This includes quantifying resources used (such as energy and raw materials), emissions released (including pollutants and greenhouse gases), and other environmental aspects (such as waste generated). The LCI phase aims to build a comprehensive inventory of all relevant environmental flows to understand the environmental impact of the product or system. This data forms the basis for the next phases of LCA, such as impact assessment and interpretation.

European norms

In Europe, Life Cycle Assessments (LCAs) for sustainability are governed by various European Norms, each tailored to various aspects of construction works. The EN 17472:2022 standard, being the most recent, focuses specifically on the sustainability assessment of civil engineering works and provides detailed calculation methods, making it particularly relevant for evaluating the environmental impact of large infrastructure projects. EN 15643:2021 is broader, covering both buildings and civil engineering works, while EN 15978:2011 is more narrowly focused on the environmental performance of buildings. EN 15804:2012, though essential, deals with Environmental Product Declarations (EPDs) for construction products and is less directly applicable to full-scale infrastructure assessments. Given its focus and recency, EN 17472:2022 is likely the most suitable for comprehensive sustainability evaluations of large civil works.

EN 17472 establishes specific methods for assessing the environmental, economic, and social performance of civil engineering works, considering their functionality and technical characteristics. It supports decision-making by providing a standardised approach that allows for the comparability of different project options. The assessment, applicable to all life cycle stages of new and existing works, as well as refurbishments, is based on Life Cycle Assessment (LCA), Life Cycle Cost (LCC), Whole-Life Cost (WLC), and other relevant data, including Environmental Product Declarations (EPDs) and additional indicators.

EN 17472 outlines that the steps illustrated in Figure 13 must be followed to assess the environmental, economic, and social performance of civil engineering works. This ensures that all necessary information is gathered and processed according to the standard requirements. It includes a total of eight steps: (1) identification of the purpose of the assessment, (2) specification of the object of the assessment, (3) use and/or development of scenarios, (4) quantification, (5) selection of data and other relevant information, (6) evaluation of the environmental, economic and social indicators, (7) Reporting and communication, and (8) verification. For further details read the standard; information about functional equivalent, system boundary, and reference period is covered in the following paragraphs.

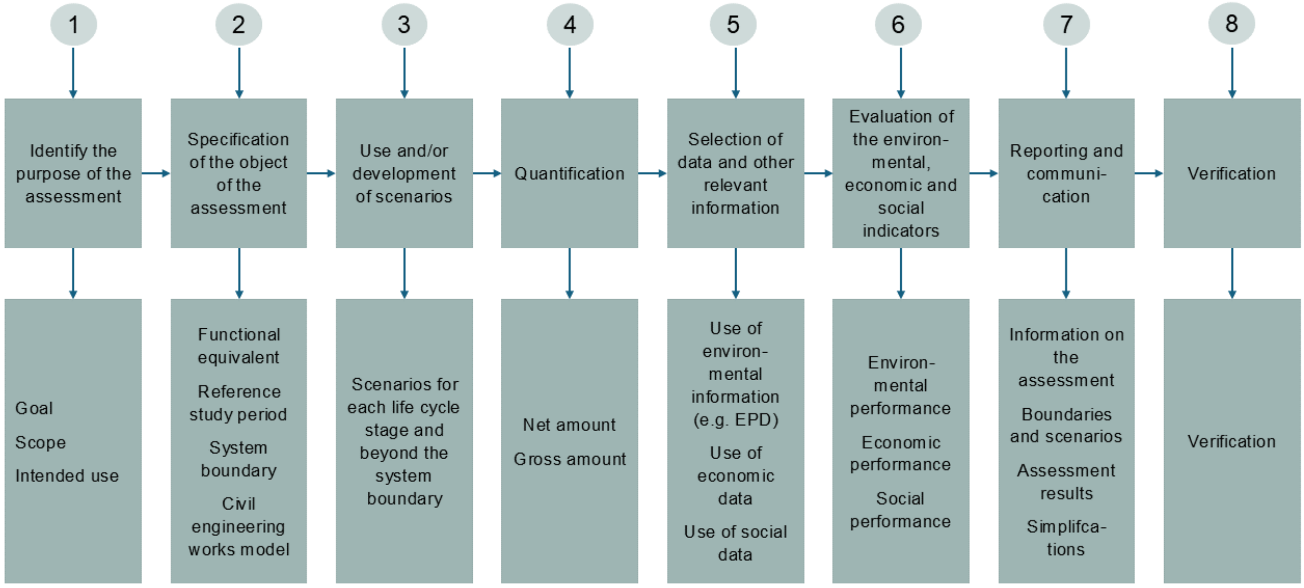


Figure 13 Steps of the assessment process

System boundary

The system boundary determines the processes that are considered for the object of assessment. In the European Norms, the system boundary is based on a modular approach, i.e. Modules A-D described below and shown in Figure 14.

- *Module A0* covers all the before-life cycle stages. This module includes planning costs, land costs, professional fees and taxes incurred.
- *Modules A1-A3* refer to the extraction and production of raw materials, transportation of raw materials to the manufacturing units, and manufacturing process at the plant.
- *Module A4* normally includes the transportation of the materials and products from the factory gate to the construction site, as well as losses due to the transportation (e.g., products damaged or lost during transportation).

- *Module A5* is the construction and installation process and includes groundworks and landscaping, storage of products, transport of persons and construction equipment to and from the site, transport within the site, temporary works, on-site production, product transformation, provision of controlled environmental conditions during the construction process, ancillary materials not considered in environmental product declarations (EPDs – e.g. formworks discarded at the end of the project), any intermediate disposal of wastes and transportation of waste during the construction and installation process
- *Modules B1-B8*, the use stage encompasses the protection, conservation, moderation, maintenance, control, and operation of the assessed object, including integrated technical systems. The assessment boundary excludes impacts, aspects, and costs related to non-civil engineering assets and unintended uses. It also excludes performance guarantees or the impacts of manufacturing cars, with the latter covered under B8. Civil engineering-related appliances are those fixed to the infrastructure, where their removal impairs the performance of the works, and their dismantling or replacement constitutes construction activities.
- *Modules C1-C4,* the end-of-life stage for a civil engineering project begins when it is decommissioned and no longer intended for use. At this point, demolition or deconstruction is treated as a multi-output process that generates materials, products, and construction elements to be discarded, recovered, recycled, or reused, with the system boundary defined by these end-of-life scenarios. A civil engineering project is considered to have reached the end of its life when all components and materials designated for removal have been cleared from the site, the site is prepared for future use (i.e., cleared and ready for new activities), and the project has been decommissioned and abandoned.
- *Module D1-D2* extends beyond the system boundary and is divided into two parts: potential resources for future use, which includes reused products, recycled materials, and energy recovery, and the benefits and loads associated with exported energy. Module D1 addresses the reuse, recycling, and energy recovery of secondary products, materials, and fuels that have economic value or have reached the end-of-waste stage and exit the system boundary. Module D2 focuses on the loads and benefits related to the exported energy from the civil engineering works, assessing the impacts of energy production that are offset by the exported energy, such as avoided average grid mix impacts.

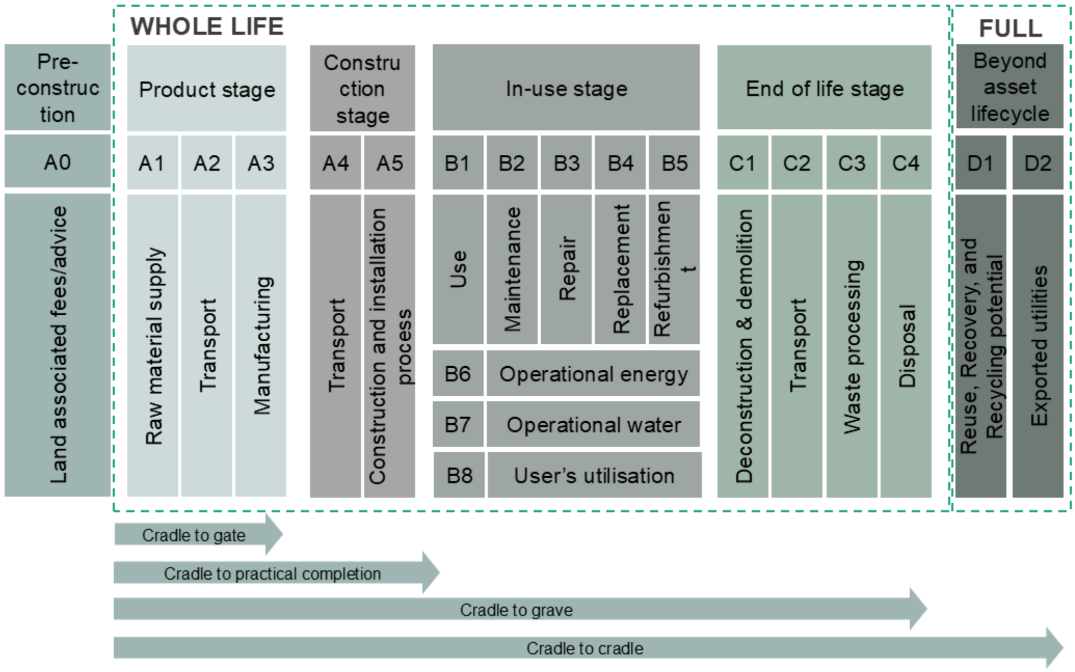


Figure 14 Impact assessment modules.

Depending on the limit of the system boundary, the technical literature uses various definitions as follows:

- *Cradle to Gate (Modules A1-A3).* Covers the life cycle stages from raw material extraction to the product leaving the factory gate.
- *Cradle to Practical Completion (Modules A1-A5).* Includes the life cycle stages from raw material extraction to the point of practical completion of the construction.
- *Cradle to Grave (Modules A-C).* Encompasses the full life cycle from raw material extraction to end-of-life disposal.
- *Cradle to Cradle (Modules A-D).* Covers the entire life cycle with the incorporation of potential resources for future use.

Functional unit

The functional unit is a measure of the function of the studied system, and it provides a reference to which the inputs and outputs can be related. For example, the functional unit for a paint system may be defined as the unit surface protected for 10 years. ISO 14040, ISO 14044 and EN 15804 define a functional unit; EN 15804 also defines a declared unit. EN 17472 and EN 15978 define a functional equivalent. The distinction between functional unit, declared unit and functional equivalent is specific to the European construction sector, as they are defined in the CEN standards.

ISO 14040 and 14044, as the basic LCA standards, define the 'functional unit' as the quantification of the performance of a product system, and specify that is used as the reference unit for the LCA and any comparative assertion. The term 'functional equivalent' is defined in EN17472 as the quantified functional and/or technical requirements for a building or civil engineering works or an assembled system, and in EN 15978 as denoting the technical characteristics and functionalities of the building that is being assessed. building type, relevant technical and functional requirements, the pattern of use and the required service life.

The term 'functional unit', as defined in EN 15804, refers to the quantification of identified functions or performance characteristics of products. The function/performance characteristics of the product are defined at the building level. The functional unit is used primarily as the reference unit for the product LCA study. It is the unit of scale or reference on which the LCA results are based and relates to the given

function of the product. In other cases, the functional unit should be defined according to the future use of the building. A functional unit comprises a function, a quantity, a duration and a quality.
The term 'declared unit' is specific to product LCAs, as defined in EN 15804. It is used instead of the 'functional unit' if the specific function of a product at the building level is not known. EN 15804 states that the declared unit shall be used if an LCA study does not cover the entire life cycle ('cradle to grave'), but only certain modules (e.g. only 'cradle to gate'). The terms should be used in line with the definitions of the standards to allow for improved consistency of LCA studies within the construction sector

Life cycle inventory

In the Life-Cycle Inventory (LCI), various lifecycle stages involve distinct inputs and outputs (Figure 15). For raw material extraction (e.g., mining and quarrying), inputs include sand, water, ore, and wood, while the outputs are environmental pollutants such as CO_2, heavy metals, SO_x, NO_x, and organic toxins. During the transport stage, inputs primarily consist of oil or fossil fuels, leading to outputs like CO2, particulate matter, SO_x, and NO_x. In the use stage, inputs involve energy and maintenance materials, and outputs include CO_2, NO_x, and potential pollutants from wear and tear. For the end-of-life stage, inputs might include land use and waste materials, with outputs including CH_4 in landfills, leaching of heavy metals, and other pollutants from decomposition. Each stage contributes to the overall environmental impact of the product or system.

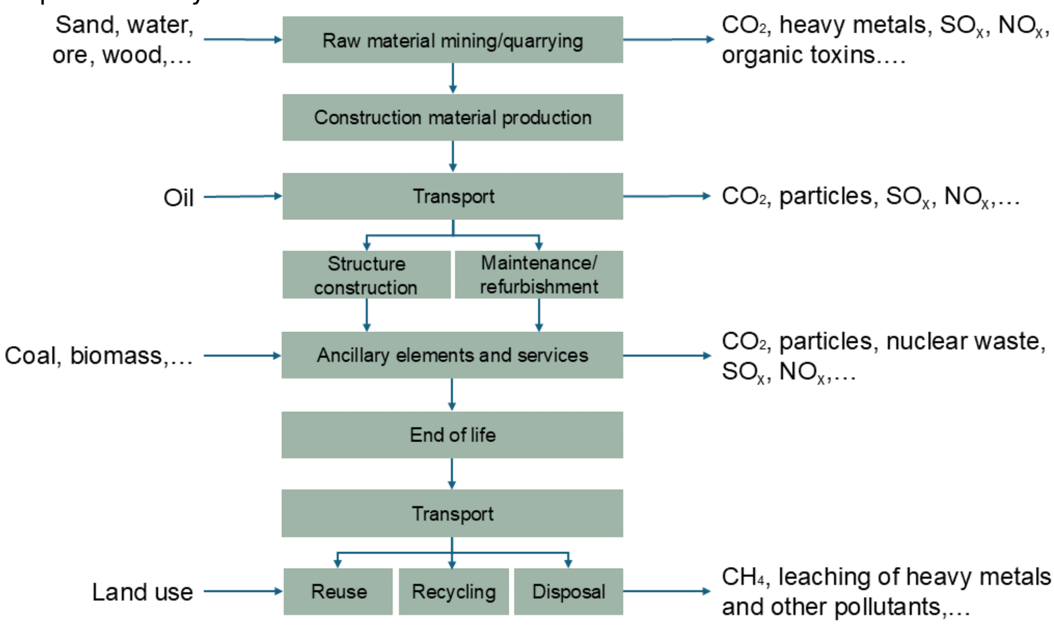


Figure 15 Inputs and outputs for various stages (modules) of the assessment

In the Life-Cycle Inventory (LCI), several comprehensive databases provide critical data for environmental assessments. Ecoinvent is a widely used database offering detailed datasets on various products, processes, and services, and is known for its extensive coverage and high-quality data (Ecoinvent Association, 2021). GaBi is another major LCI database that provides robust data for life cycle assessment with a focus on industrial processes and materials (Sphera Solutions, 2021). USLCI offers a range of datasets specific to the U.S. market, including energy, materials, and waste management (U.S. Environmental Protection Agency, 2021). ELCD (European reference Life Cycle Database) offers European-specific datasets covering a wide array of products and processes (European Commission, 2021). These databases are essential tools for conducting accurate and reliable LCI studies, offering valuable inputs for impact assessment and decision-making.
While LCI databases such as Ecoinvent, GaBi, USLCI, and ELCD are essential for life cycle assessments, they do have limitations. These databases may lack comprehensive coverage for all geographical regions, industries, or niche products, with databases like USLCI focusing primarily on U.S. data (Curran, 2017). Additionally, the data may become outdated due to evolving technologies and market conditions,

affecting databases such as ELCD and Ecoinvent (Wolf et al., 2010). Variability in data quality and reporting methods can lead to inconsistencies, as observed in databases like GaBi and Ecoinvent (de Eicker et al., 2010). Moreover, many databases use generalised data that may not accurately reflect specific cases or local conditions (Frischknecht et al., 2015). Finally, accessibility can be an issue, as some databases like GaBi may require expensive subscriptions, while free databases like USLCI may have more limited datasets (de Eicker et al., 2010).

Part of this critical data in the databases, Environmental Product Declarations (EPDs) play a significant role. EPDs are standardised documents that provide transparent and comparable information about the environmental impacts of products or services. They are based on Life Cycle Assessment (LCA) and include data on various environmental aspects, such as resource use, emissions, and waste, across the life cycle of a product or system. EPDs are created following specific standards, such as EN 15804, and are intended to help stakeholders, including consumers, designers, and regulators, make informed decisions by offering detailed insights into the environmental performance of products. They typically cover categories such as global warming potential, energy consumption, and other relevant impact indicators (described in the following paragraphs), making them useful for assessing and comparing the sustainability of various products. These are typically available on the producer website or in EPD libraries (Environdec, 2024).

Impact assessment

Once the system boundary, functional unit, and inputs/outputs are established, the Impact Assessment (IA) quantifies the potential environmental impacts of a product or service. It considers a broad range of impacts, including climate change, resource depletion, ecotoxicity, and human health. Using standardised methods and characterisation factors, the IA assesses these impacts over several impact categories. This provides valuable information for decision-making and helps identify opportunities for improvement.

Impact categories are specific types of environmental effects that are assessed in a Life Cycle Assessment (LCA) to evaluate the potential environmental impact of a product or service. Common impact categories include climate change, ozone depletion, resource depletion, human toxicity, ecotoxicity, and acidification, among others. The exact number of impact categories can vary depending on the methodology and standards used. For example, the ISO 14044:2006 standard identifies several key impact categories, and the ReCiPe method, a widely used impact assessment method, includes 18 impact categories. Ecochain (2024) includes 15 categories, whilst frequent practice in the civil engineering works assessments accounts for a single category, the global warming potential.

The ReCiPe method is a comprehensive framework used for Life Cycle Impact Assessment (LCIA), designed to evaluate the environmental impacts of products and services (Figure 16). It categorises impacts into midpoint indicators, which measure environmental effects at an intermediate stage, and endpoint indicators, which assess the final damage to areas such as human health, ecosystem quality, and resource availability. The method employs a hierarchical approach to link midpoint impacts to endpoint damages, providing a detailed understanding of environmental effects. ReCiPe includes two versions: ReCiPe 2008, the original version with both midpoint and endpoint categories, and ReCiPe 2016, which offers refined methodologies and improved data for greater accuracy (Huijbregts et al., 2017).

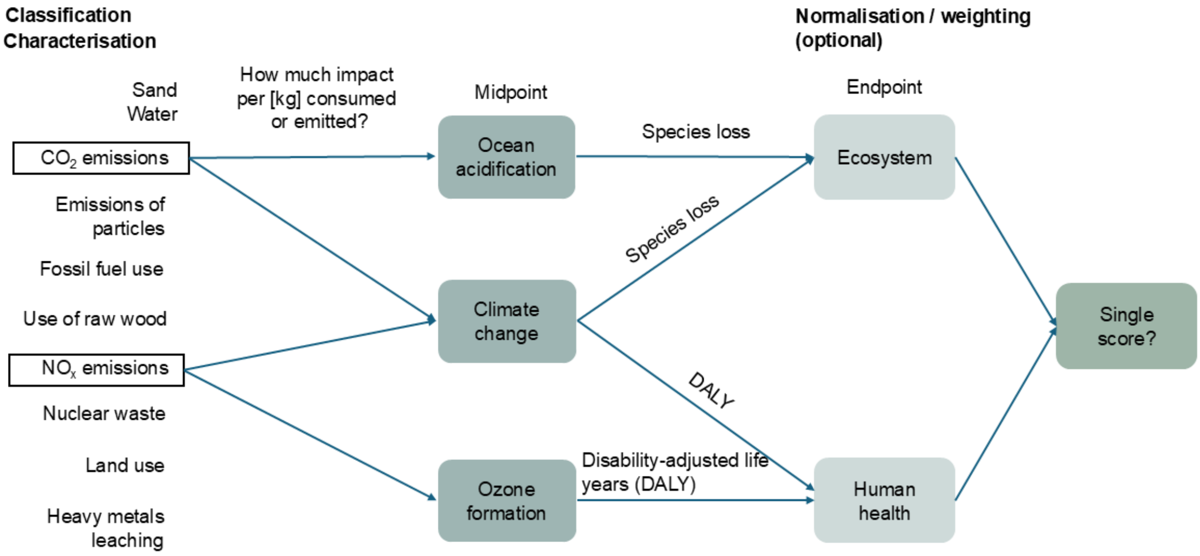


Figure 16

Before assessing the mid-point indicators, classification and characterisation of the LCI is carried out. Classification involves assigning the life cycle inventory (LCI) data to specific impact categories. For instance, emissions of CO_2 are classified under the global warming potential category, while NOx emissions are classified under acidification potential. Classification helps organise data according to the types of environmental effects they may cause. Once data is classified, characterisation quantifies the impact of each classified input or emission by applying characterisation factors. These factors convert the classified data into impact scores for each category. For example, the amount of CO_2 emissions is multiplied by its global warming potential factor to assess its contribution to climate change.

After obtaining the endpoint indicators, normalisation and weighting are sometimes carried out for communication purpose and decision-making. Normalisation involves scaling the impact results to a common reference, usually by comparing them to a baseline or average impact, such as per capita impacts for a specific region or sector. This helps to contextualise the results and make them more understandable by showing how the impacts of a product or process compare to typical values. Weighting assigns relative importance to different impact categories based on value choices or policy objectives. It combines the normalised impacts into a single score by applying weights, which reflect the relative significance of each impact category. This helps in decision-making by highlighting the most critical impact areas according to predefined criteria or stakeholder preferences.

Table 1 shows a detailed description of 15 impact categories which are commonly used in Environmental Impact Assessments. Depending on the type of the project, some of the categories have limited value for civil engineering works. The categories with the greatest impact are climate change, depletion of resources and land use. Due to the complexity of the complete Impact Assessment, the construction sector tends to focus on a single impact category, climate change, or the Global Warming Potential (GWP). The Global Warming Potential (GWP) is a factor that measures the radiative forcing impact of a greenhouse gas relative to carbon dioxide (CO_2) over a specific period. GWP considers the effects of various greenhouse gas (GHG) on the climate (IPCC, 2013). Greenhouse gases (GHGs) are atmospheric gases, both natural and anthropogenic, that absorb and emit radiation at infrared wavelengths, affecting the Earth's radiative balance. GHG emission refers to the total mass of these gases released into the atmosphere during a given period. Although the main measure for GWP is CO_2, the effects of other GHGs (e.g. methane, nitrogen dioxide) on climate change are represented by a CO_2 equivalence (Horvath, 2005).

Table 1 Ecochain impact categories

Impact Category / Indicator	Unit	Description

Climate change – total, fossil, biogenic, and land use	kg CO2-eq	Indicator of potential global warming due to emissions of greenhouse gases to the air. Divided into 3 subcategories based on the emission source: (1) fossil resources, (2) bio-based resources, and (3) land use change.
Ozone depletion	kg CFC-11-eq	Indicator of emissions to air that destroys the stratospheric ozone layer
Acidification	kg mol H+	Indicator of the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulphur oxides
Freshwater eutrophication	kg PO4-eq	indicator of the enrichment of the freshwater ecosystem with nutritional elements, due to the emission of nitrogen or phosphor-containing compounds
Marine eutrophication	Kg N-eq	Indicator of the enrichment of the marine ecosystem with nutritional elements, due to the emission of nitrogen-containing compounds.
Terrestrial eutrophication	mol N-eq	Indicator of the enrichment of the terrestrial ecosystem with nutritional elements, due to the emission of nitrogen-containing compounds.
Photochemical ozone formation	kg NMVOC-eq	Indicators of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight.
Depletion of abiotic resources – minerals and metals	kg Sb-eq	Indicator of the depletion of natural non-fossil resources.
Depletion of abiotic resources – fossil fuels	MJ, net calorific value	Indicator of the depletion of natural fossil fuel resources.
Human toxicity – cancer, non-cancer	CTUh	Impact on humans of toxic substances emitted to the environment. Divided into non-cancer and cancer-related toxic substances.
Eco-toxicity (freshwater)	CTUe	Impact on freshwater organisms of toxic substances emitted to the environment.
Water use	m3 world eq. deprived	Indicator of the relative amount of water used, based on regionalised water scarcity factors.
Land use	Dimensionless	Measure of the changes in soil quality (Biotic production, Erosion resistance, Mechanical filtration).
Ionising radiation, human health	kBq U-235	Damage to human health and ecosystems linked to the emissions of radionuclides.
Particulate matter emissions	Disease incidence	Indicator of the potential incidence of disease due to particulate matter emissions

In general practice, carbon dioxide equivalent (CO_2e) is typically the sum of embodied carbon and operational carbon. Embodied carbon encompasses the total greenhouse gas emissions associated with a material throughout its entire life cycle, including extraction, manufacturing, construction, maintenance, and end-of-life disposal. Operational carbon refers to the carbon dioxide emissions produced during the operational or in-use phase of the material. Other definitions may apply, particularly in the context of infrastructure carbon management. These are described in the following sections.

In simplified impact assessments, commonly used across various industry sectors, the intricate life-cycle assessment is streamlined into a series of straightforward mathematical operations. This simplified approach involves: (1) defining goals, scope, system boundaries, functional unit, and reference period (e.g., evaluating embodied carbon according to EN17472 for an integral bridge over a

120-year design life, treating the entire asset as a functional equivalent); (2) estimating the quantities of materials, products, and processes involved; (3) calculating carbon equivalent emissions for each material/product and process, then summing them to determine the total carbon; and (4) interpreting the results and refining the assessment as necessary.

In practice, various carbon assessment tools are available, often in the form of spreadsheets with embedded mathematical functions and material impact data. Examples include the Structural Carbon tool, the National Highways Carbon Emissions Calculation Tool, the Raul RSSB Carbon Tool, the Asphalt Pavement Embodied Carbon Tool, and the Steel Bridges Carbon Calculator developed by Atkins. The links are available in the supporting slides.

Summary

Life Cycle Assessment (LCA) was recognised as a key method for evaluating the environmental impacts of products and projects throughout their life cycle. This section introduced the definition and purpose of LCA, emphasising its role in sustainable decision-making. The key stages of LCA—goal and scope definition, inventory analysis, impact assessment, and interpretation—were explored, along with an overview of various LCA software and tools to improve assessment accuracy.

Life Cycle Assessment (LCA), as defined by ISO 14040:2006, evaluates the environmental impacts of a product throughout its life cycle. It focuses on environmental aspects, with additional tools needed for economic and social factors. The iterative process includes stages (modules) and phases (steps), collecting data on inputs and outputs to assess their environmental impact, such as contributions to global warming and pollution.

EN 17472:2022 is the most recent European standard for assessing the sustainability of civil engineering works, providing detailed methods for evaluating environmental, economic, and social impacts. It supports decision-making by enabling comparability across projects, making it particularly relevant for large infrastructure assessments, while other norms address different construction aspects. The system boundary defines which processes are included in the assessment and follows a modular approach in European Norms. The functional unit measures the function of the system, linking inputs and outputs. Simplified impact assessments streamline LCA into basic steps: defining goals, scope, boundaries, and units; estimating materials and processes; calculating carbon emissions; and interpreting results.

Activity 3. Carbon emissions management

This activity will provide an overview of embodied carbon emissions and their significance in infrastructure projects. The material explores various strategies to minimise these emissions and discuss the role of carbon management and whole-life costing in achieving sustainable outcomes.

The Infrastructure Carbon Review (HM Treasury, 2013) addressed whole life carbon for infrastructure projects, distinguishing between carbon under the control and influence of asset owners and managers. Since then, decarbonisation principles have advanced in response to heightened urgency from the COP21 Paris Agreement. As of 2023, there is a global push towards a net zero-carbon world by 2050, incorporating resilience and biodiversity goals. This shift has intensified the challenge for the built environment, requiring significant changes at the system level through collaborative efforts. Historically, carbon management for buildings and infrastructure has been handled separately, with varying terminology, standards, and definitions. It becomes more prominent the need to view infrastructure and buildings together due to their interdependencies. PAS2080:2023 scope is to manage carbon to reduce whole-life emissions in the built environment, aligned with the net zero carbon transition and recognise the importance of balancing climate adaptation and circular economy principles to bring wider co-benefits.

In line with the earlier points, assets are part of complex, interconnected networks and systems. A building or infrastructure asset exists within a network, which itself is part of a broader system (see the diagram at the bottom right). Figure 17 introduces the work stages in PAS 2080, which are similar to those in the Value Toolkit developed by the Construction Innovation Hub. These work stages can be adopted for all infrastructure levels (asset, network, system). The stages include: (1) need, (2) optioneering, (3) design, (4) delivery, (5) operation, and (6) purpose and performance review. These stages of the infrastructure lifecycle align with those in BS 8536:2022, which addresses design, manufacture, and construction for operability, with an additional end-of-life stage. They also align with the work stages for the design and construction process of buildings as outlined in the Royal Institute of British Architects' Plan of Work (RIBA, 2020). While other sector-specific definitions of work stages may differ, this approach is applicable and suitable for both sustainability and circularity assessments.

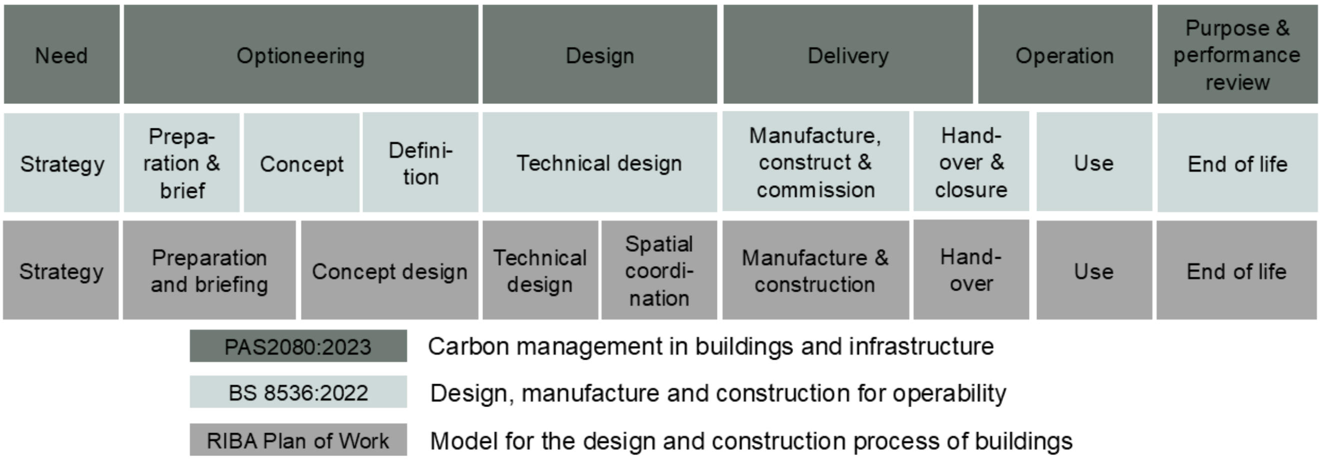


Figure 17 Work stages

In the earlier activity, there was a reference to various impact categories, noting that carbon dioxide emissions are typically divided into embodied and operational carbon, a terminology commonly used in the context of buildings. PAS 2080 introduces new terms, including 'capital', 'user', and 'optional' carbon. Capital carbon is defined as the emissions and removals associated with the creation and end-of-life treatment of an asset, network, or system, and optionally with its maintenance and refurbishment. This term was introduced to align carbon assessment with the cost management and expenditure profile of projects and programmes of work.

According to the standard, 'user carbon' refers to the greenhouse gas emissions associated with the utilisation of an asset, network, or system by its users, and the service it provides during operation. Maintenance and refurbishment emissions are included as 'optional' under the capital carbon definition because, depending on the assessment methodology, they could also be classified as 'operational carbon' emissions. The standard also acknowledges terms like 'embodied carbon' and 'upfront carbon' in line with other existing life cycle assessment standards and guidance. The impact assessment itself would follow the same steps, as PAS2080:2023 covers carbon management throughout the infrastructure lifecycle, rather than explicit assessment of the emissions.

Decarbonisation principles

Decarbonisation must be approached from the system level downwards, requiring close collaboration across the value chain, especially in the context of a net zero transition. PAS 2080 recognises this systems approach in its carbon management requirements, acknowledging that governments, regulators, and in some cases, major asset owners and managers, often hold the most control at the system level.

Figure 18 in the slide illustrates the nested relationship of an asset within a network and a broader system, highlighting the varying levels of control and influence that each value chain member has to drive whole-life carbon reductions, with opportunities for projects and programmes at each level. PAS 2080 also emphasises that whole-life carbon assessment is essential for effective carbon management.

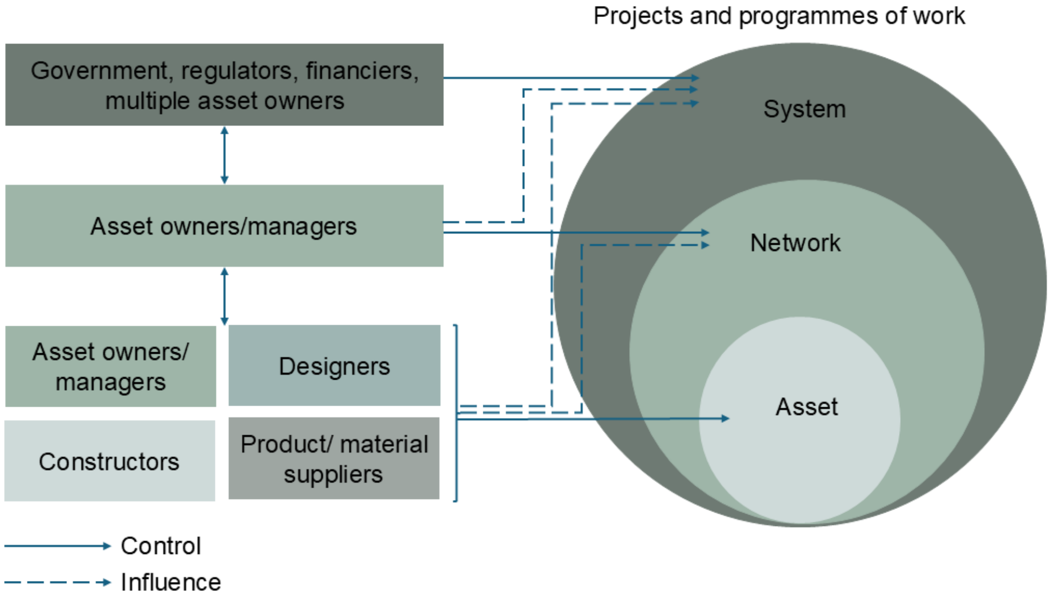


Figure 18 Stakeholders involved in carbon management (adapted from PAS2080:2023).

In the pursuit of net zero, it is essential for the value chain, especially asset owners and managers, to acknowledge the complex interdependencies and synergies between decarbonisation, other pressing issues such as climate adaptation and biodiversity loss, and the social and economic priorities specific to each context. Projects and programmes in the built environment must address these challenges holistically. The carbon management process outlined in PAS 2080 offers a systematic approach, enabling value chain members to place relevant criteria at the centre of decision-making for the future benefit of our planet and society. The carbon management principles apply to both building and infrastructure projects and programmes. Central to these principles is the understanding that no built environment asset works in isolation; its construction, operation, and use both affect and are affected by the networks and systems it is part of. Similarly, the decarbonisation principles extend across all value chain members, each bearing responsibility for managing carbon within the infrastructure.

All value chain members are responsible for managing carbon, which includes the following actions:

- Identify all activities that result in carbon emissions or removals within their control or influence, at the asset, network, and system levels, as illustrated in Figure 19.
- Recognise interdependencies and relationships between their project or programme and the broader network and system, engaging stakeholders to uncover carbon reduction opportunities and risks.
- Prioritise nature-based solutions that reduce whole-life carbon emissions and enhance carbon removal, while also delivering co-benefits.
- Collaborate with other value chain members and stakeholders, such as planning authorities, financiers, and regulators, to align carbon reduction efforts and maximise decarbonisation opportunities across projects, programmes, and, where possible, entire sectors or regions.
- Determine the work stages where they have control or influence over low-carbon solutions, prioritising significant opportunities or risks that impact system-wide decarbonisation.
- Assess emissions and removals according to the whole life carbon framework in the figure.
- Ensure that the accuracy of carbon assessments aligns with the stage of the project or programme to support informed decision-making.
- Integrate whole-life carbon reduction into their decision-making processes.

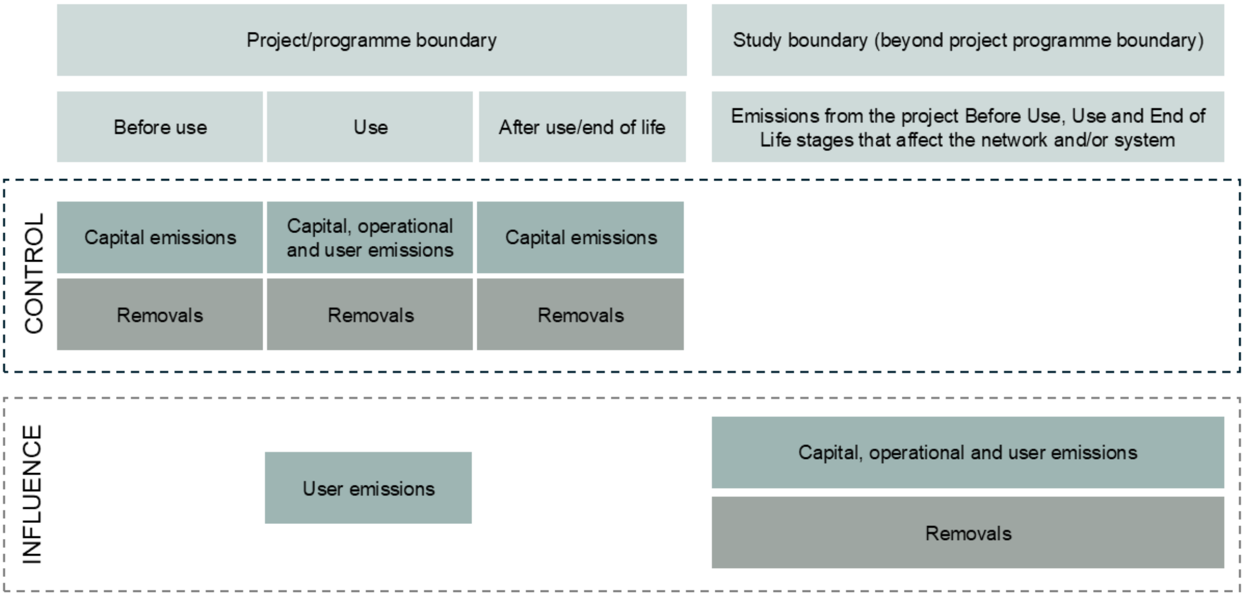


Figure 19 Whole-life carbon decision-making (adapted from PAS2080:2023).

Additionally, asset owners/managers and designers should Identify the carbon implications of climate resilience, or the lack thereof, at the asset, network, or system level, and incorporate these into the whole life carbon framework for decision-making. They should also collaboratively work with other value chain members and stakeholders to find solutions that deliver the required climate change resilience with the lowest whole-life carbon, including carbon savings from avoiding future recovery efforts.
All stakeholders should adhere to the carbon reduction hierarchy, as illustrated in Figure 20, prioritising actions to reduce whole-life carbon emissions (capital, operational, and user). The actions are as follows:

- *Avoid*. Align project or programme outcomes with the net zero transition at the system level and evaluate the fundamental need at the asset or network level. This may involve exploring alternatives to avoid new construction, such as reusing, retrofitting, or repurposing existing assets or networks.
- *Switch*. Assess and adopt alternative solutions that reduce whole-life emissions, such as different scopes, design approaches, materials, or technologies, while still meeting whole-life performance requirements. This might include innovative models that balance capital investment, resource use, and operational and user efficiency.
- *Improve*. Implement solutions that enhance resource use and extend the design life of an asset or network. Apply circular economy principles to evaluate materials and products for their potential reuse or recycling after end-of-life and focus on efficiency improvements throughout the use stage of the asset or network.

When selecting low-carbon solutions, priority should be given to those that support decarbonisation at the network and system levels.

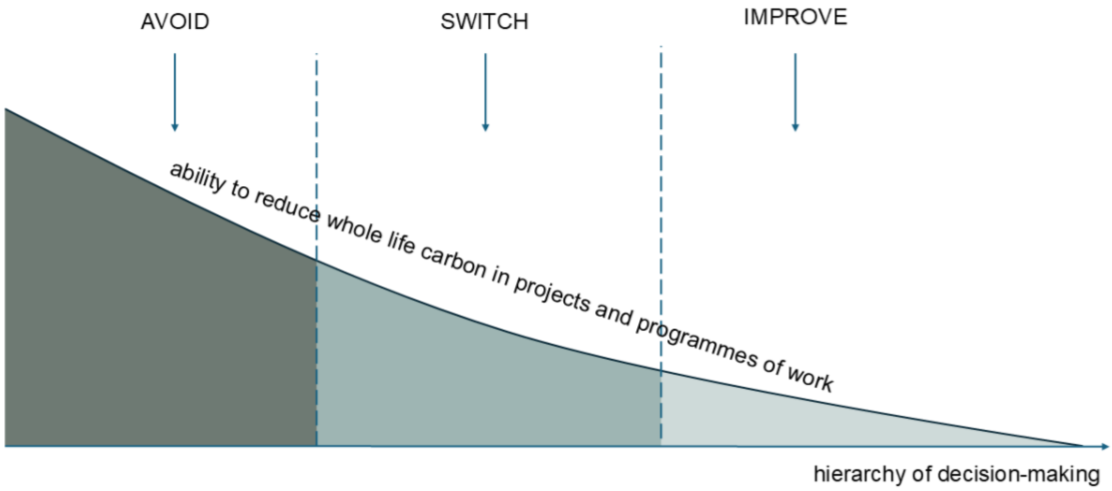


Figure 20 Carbon hierarchy reduction ((adapted from PAS2080:2023).

At each work stage, value chain members are expected to establish and implement a carbon management process, including the below actions. Additional requirements apply to each stakeholder group.

- Understand and prioritise the carbon management requirements set by the asset owner/manager for the project or programme of work.
- Identify and act on opportunities to reduce whole-life carbon where they have control or influence, following the carbon reduction hierarchy, with an emphasis on early intervention.
- Prioritise solutions that most effectively contribute to system-wide decarbonisation.
- Challenge existing practices to enable whole-life carbon reduction, including revisiting scope, strategy, standards, design approaches, and cost considerations.
- Collaborate with stakeholders and value chain members to implement low-carbon solutions.
- Assess and document whole-life carbon emissions and removals within their control, tracking reductions against established baselines and targets.
- Identify low-carbon alternatives at each stage of the carbon reduction hierarchy, incorporating nature-based solutions and circular economy opportunities where applicable.
- Report carbon removal activities separately from carbon emissions and reductions.

Impact assessments

Whole-life assessments of an asset, network, or system should adhere to the procedures previously discussed. This involves using appropriate methodologies, such as those outlined in EN 17472, EN 15978, and EN 15804, to assess impacts. It is also essential to identify and address limitations in existing methods and to compare different scenarios or options using consistent methodologies. While the impact assessment follows similar steps, PAS 2080 focuses on carbon management throughout the infrastructure lifecycle rather than solely on explicit emissions assessments.

When assessing carbon emissions over the whole life of an asset, network, or system to inform decision-making, the main steps include establishing a comprehensive study that encompasses all emission sources and removals as per the whole life carbon framework, ensuring it extends beyond the project or programme boundary to consider impacts on the broader network and system. Then using an appropriate methodology, assess emissions and removals from all sources within the control and influence of value chain members throughout all stages of the delivery process. Primarily for large projects, include the assessment of emissions and removals associated with land use changes, such as nature-based and climate resilience solutions, in the decision-making process, but exclude market-based offsets from the assessment boundary.

It is recognised that the accuracy of the carbon assessments depends on the availability of carbon and asset data (Figure 21). This improves the delivery process as more data is available. During the need and optioneering stages, one is expected to use a methodology that prioritises emissions and removals that could decide the lowest carbon option, considering impacts beyond the project boundary. This might involve creating new assets or repurposing existing ones. At the design, delivery, and operation stages, it is expected to apply an appropriate methodology to evaluate emissions and removals in sufficient detail, considering the impact of the project on the network and system unless it is irrelevant for decision-making.

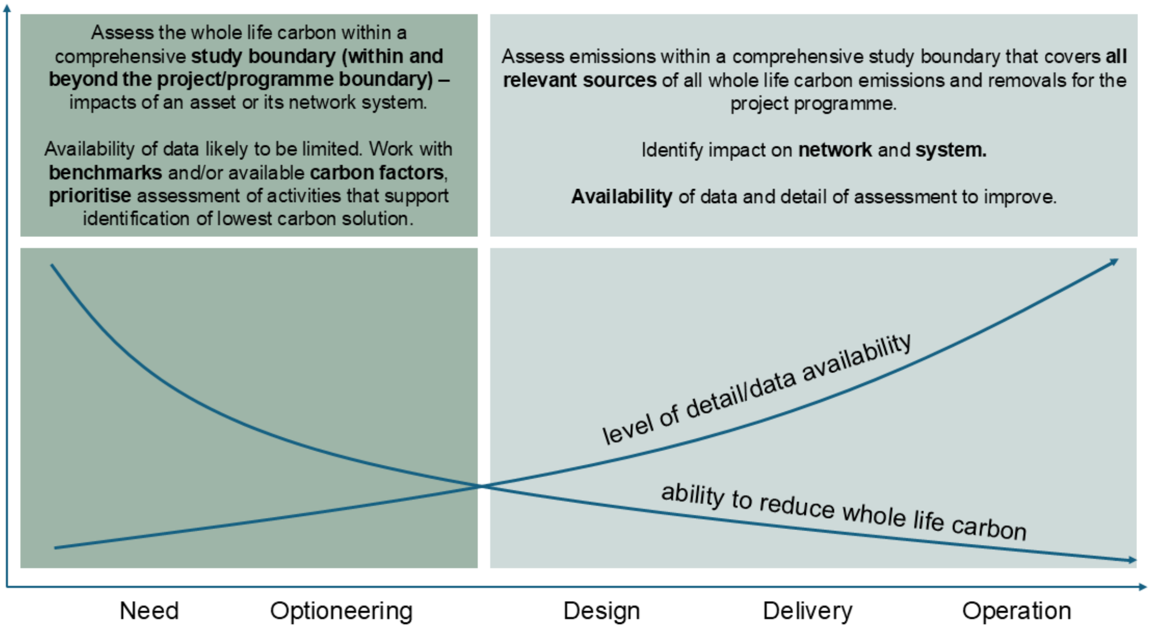


Figure 21 Capability to influence carbon reduction and data availability versus work stages.

Setting targets and establishing baselines, along with robust monitoring and reporting, are fundamental to effective carbon management. All stakeholders must collaborate to set carbon reduction targets based on clear baselines for accurate performance assessment. These targets should be aligned at the system level and with network and asset-level goals, recognising that asset-level targets are essential for achieving system-wide net zero objectives. Effective carbon management requires frequent, transparent reporting to track progress and guide decision-making, ensuring that reports support whole-life carbon management and inform future improvements.

Life cycle costing

Life-cycle costing (LCC) is a financial analysis method that evaluates the total cost of owning and operating an asset over its entire life span. It includes all costs from acquisition, operation, maintenance, and disposal, offering a comprehensive view of the financial implications of different options or decisions. This approach helps in comparing various alternatives by considering not just the initial costs but also future expenses and benefits, thus supporting more informed and sustainable decision-making. ISO 15686-5:2017 (Life-cycle costing' for buildings and constructed assets) focuses on the principles and methods for life-cycle costing (LCC) in the context of buildings and constructed assets. This standard provides a framework for assessing the total costs associated with the lifecycle of a building, from initial design and construction through to operation, maintenance, and eventual demolition or decommissioning (Figure 22).

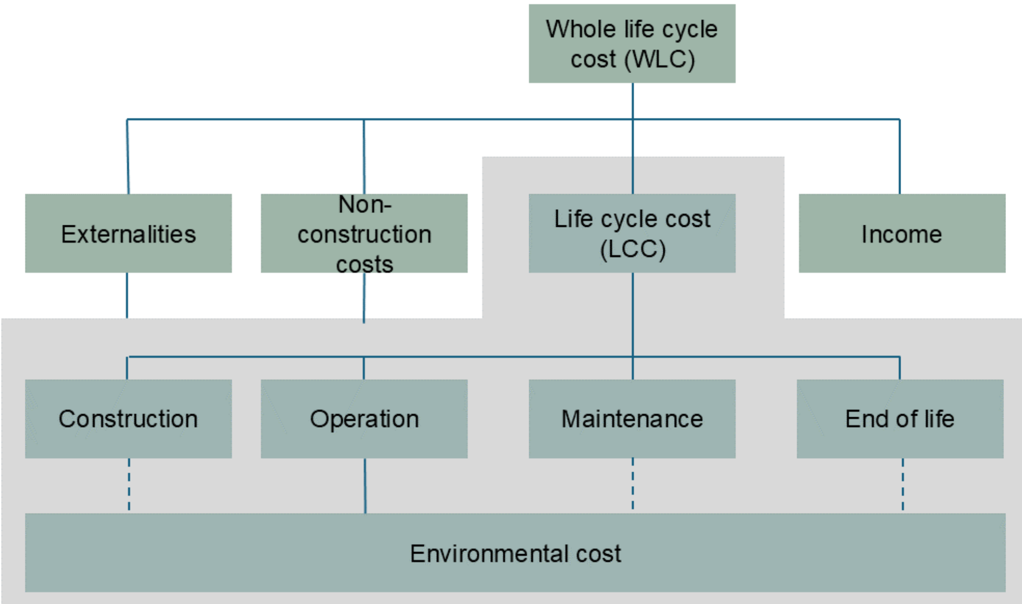


Figure 22 Whole life costing model.

The primary aim of the code is to offer guidance on how to evaluate and compare the costs of distinctive design and construction options, incorporating both capital and operational expenses. It addresses aspects such as cost estimation, cost management, and the integration of life-cycle cost considerations into decision-making processes. By following this standard, stakeholders can better understand the financial implications of their choices, aiming to optimise value for money and support sustainable development practices.

ISO 15686-5:2017 focuses on the principles and methods for life-cycle costing (LCC) in the context of buildings and constructed assets. This standard provides a framework for assessing the total costs associated with the lifecycle of a building, from initial design and construction through to operation, maintenance, and eventual demolition or decommissioning. According to the code, the Whole life cycle cost model includes the life cycle cost (LCC) of the asset, and the externalities, non-construction costs and income. The LCC include initial costs such as design, construction, and commissioning; operating costs for energy, water, and other operational needs; maintenance costs covering routine upkeep, repairs, and replacements; and end-of-life costs related to decommissioning, disposal, or recycling the asset once its service life concludes.

ISO 15686-5:2017 gives guidance on dynamic investment calculations. These dynamic methods are characterised by recording cash inflows and outflows at one point in time. Another standard that provides guidance on life cycle and whole life costing is EN16627:2015. In this standard Life Cycle Costs refers only to costs, and Whole Life Costs includes both expenditure and income for assessing life cycle success/economic efficiency. The reader is encouraged to read the two standards for further details.

Summary

This activity reviewed embodied carbon emissions and their impact on infrastructure projects, focusing on strategies to reduce emissions through effective carbon management and whole-life costing. Historically, carbon management for buildings and infrastructure was handled separately, but a unified approach is now essential due to their interdependencies. PAS2080:2023 aims to manage whole-life emissions in the built environment, aligning with net zero targets and integrating climate adaptation and circular economy principles. It outlines stages—need, optioneering, design, delivery, operation, and performance review—applicable across infrastructure levels, comparing with work stages of BS 8536:2022 and the RIBA Plan of Work (2020).

PAS2080:2023 introduces 'capital', 'user', and 'optional' carbon to align carbon assessments with cost management. Capital carbon includes emissions from creation and end-of-life treatment, while user carbon refers to emissions during use. Effective decarbonisation requires a holistic approach involving all value chain members, addressing the interplay between decarbonisation, climate adaptation, and social priorities. Life-cycle costing (LCC) evaluates the total financial impact of an asset, including acquisition, operation, maintenance, and disposal costs. ISO 15686-5:2017 and EN16627:2015 providing guidance on LCC evaluation.

Activity 4. Case study on critical infrastructure

In this learning activity, the selection of databases, life-cycle inventories, and assessment steps essential for evaluating upfront carbon emissions in both conventional and sustainable solutions will be explored. Selected industry case studies will be examined to understand practical approaches to infrastructure carbon management, providing insights into how these methodologies can be applied effectively in real-world scenarios. The activity largely refers to the approaches adopted in EN17472:2022 'Sustainability of construction works', recognised as the most relevant European Norm for infrastructure projects. As mentioned in previous activities, the system boundary is based on a modular approach (Modules A-D). In the next sections, simplified procedures to evaluate embodied carbon at the design stage will be covered.

Simplified assessment procedures

The simplified impact assessment outlined in this document follows these steps: (1) define the goal, scope, system boundaries, functional unit, and reference period (e.g., evaluate embodied carbon to EN 17472 for a 3-span bridge over a 120-year design life for modules A1-A5 from cradle to practical completion, considering the entire asset as a functional equivalent); (2) estimate quantities of materials, products, and processes involved; (3) calculate the carbon equivalent emissions for each material/product and process, then sum them to determine the total carbon footprint; (4) interpret the results and refine the assessment as necessary. This process can be implemented using the carbon tools discussed in Activity 2, with reference to the Structural Carbon tool and the supporting documentation by Gibbons et al., (2022).

In evaluating the inventory, the data flows can be assessed per component (e.g. beam, slab) and can adopt use established functional units for materials and processes, e.g., 1.0 m^3 for concrete or 1.0 kg for steel (Sabău et al., 2021). These are subsequently converted into carbon emissions, based on the estimated bills of quantities and corresponding carbon equivalent factors. The bill of quantities including the materials, on-site activities and transportation can be evaluated based on the established methods typically used for bidding (Spain, 2014). The embodied carbon factors are typically directly embedded into the carbon tool calculator, or existing databases such as the ICE Database (Circular Ecology, 2023) can be adopted. The embodied carbon factors are typically for Modules A1-A3, however, the system boundary may vary, and the user is expected to account for this variation.

Module A4 addresses the transportation of materials and products from the factory to the construction site, as well as the transport of construction equipment like cranes and scaffolding. While Module A4 emissions can be substantial for heavy civil works, they are generally minor for building projects. Transportation often involves multiple stages across different modes of transport. To mitigate both Module A4 and overall project emissions, reusing locally sourced components, materials, or products and minimising transport distances can be highly effective.

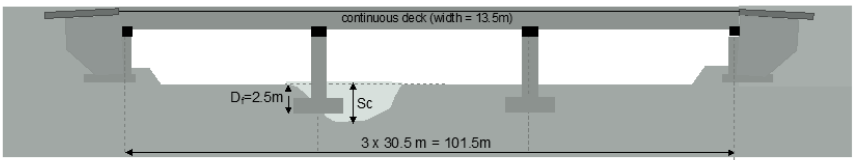
In this simplified approach, Module A5 is divided into two categories A5w for waste and A5a for machinery and temporary site office. For the waste submodule A5w, the procedure includes the multiplication of a waste factor by the sum of the carbon factors associated with the production (A1–A3), transportation to the site for construction (A4), transportation away from the site for waste processing (C2), and waste processing or disposal (C3–C4) for a product. The waste rate and waste factors can be taken from the WRAP Net Waste Tool. Site activity emissions (A5a) can be estimated based on on-site electricity consumption and fuel use and should be monitored throughout construction to ensure an accurate as-built embodied carbon calculation at practical completion. Data collected on-site activity emissions can also inform estimates of A5a emissions in future projects, including factors such as excavation and temporary works.

For Modules B and C, similar approaches to those used in Module A should be applied on a case-by-case basis. The carbon factor for Module B4 is calculated by multiplying the number of times a component is replaced during the life cycle of the asset by the sum of the carbon factors for life cycle modules A1–4, A5w, and C2–C4. Modules C1–C4 generally represent a small percentage of structural embodied carbon throughout the life cycle, unless timber products are utilised. The integration of various processes and materials in a specific module will depend on the standard adopted from the impact assessment. It is important that exact guidance is followed, and a mix and match approach between various standards is avoided.

Most materials belonging to the biological cycle have the capability of carbon sequestration. As trees grow, they sequester carbon dioxide from the atmosphere through photosynthesis, temporarily storing the carbon within timber. This stored carbon, known as 'biogenic carbon,' is released at the end of the timber life through burning or decomposition, becoming a greenhouse gas again. While the production of timber structures emits fossil carbon, the biogenic carbon is transferred into the structure during construction. At the end of its life, biogenic carbon may be released through incineration, decomposition, or transfer for reuse. Although locking biogenic carbon in timber structures benefits the climate if the carbon stays in the structure, it does not offset the immediate fossil carbon emissions from production. The amount of sequestered carbon depends on the species, but in the absence of product-specific data, biogenic carbon sequestered can be assumed as −1.64kgCO_2e per kg of timber.

Assessment case study

The case study involves a benchmark transport asset, specifically a typical river-crossing 3-span bridge with shallow foundations, assessed under nine flood scenarios (Figure 24). Vulnerability for both the as built and deteriorated asset is estimated using fragility functions (Mitoulis et al., 2023, 2024). Asset recovery is evaluated through restoration (structural capacity) and reinstatement (traffic capacity) models. Restoration tasks are linked to various construction works and a bill of quantities, incorporating materials, on-site activities, and transportation, all based on established methods. Evaluation of the environmental impacts adopted the principles from EN 17472:2022 for civil engineering works.



S_c - scour depth
S_c / D_f - scour to foundation depth ratio
C_{pf}: post-flood capacity,
C_o: original capacity

Figure 23 Case study

Environmental impact modelling

To evaluate the environmental impacts associated with materials, systems, and works within a system boundary, GWP measured in tCO2e was considered. For brevity, this is referred to as carbon in this paper and considers the GWP due to fossil as for construction works the biogenic emissions are insignificant, those associated with land use are less than 5 % of the GWP total and can be disregarded. The system boundaries adopted here correspond to a 'cradle-to-practical completion' approach (A1-A5). The emissions are divided into the following groups: (1) the capital (upfront) emissions, which correspond with the carbon associated with the construction works included in the restoration tasks at the stages shown below; (2) the user (ancillary) emissions refer to traffic re-routing and other similar emissions.

The data flows are assessed per restoration work and use established functional units for materials and processes, e.g., 1.0 m^3 for concrete or 1.0 kg for steel. These are subsequently converted into carbon emissions, based on the estimated bills of quantities and corresponding carbon equivalent factors listed in Table 1. The assumptions for estimating quantities and equipment use are shown below. The construction equipment fuel consumption rate is based on manufacturer datasheets. The emissions are assessed by multiplying the bill of quantities ($Q_{i,m}$) with the corresponding embodied carbon factor ($F_{i,m}$) and a scalar factor to account for the restoration task duration (λ_f=1 for mean durations). The subscript i indicates the material or process, whilst subscript m is for the life-cycle phase (materials, onsite activities, or transport).

A baseline analysis is conducted first to consider the main materials, construction techniques, and procedures for each restoration task. This includes in-situ concrete with cement as the only binder and new reinforcing and prestressing rebars. The same strategies are analysed with low-carbon solutions to minimise emissions for carbon-intensive tasks. This reduction is achieved by replacing materials from virgin sources with low-carbon materials and using biofuel blends for construction equipment. The main conventional construction materials are substituted by low-carbon alternatives including fly ash and GGBS in concrete. Steel rebars and tendons have 97% recycled steel obtained through electric arc furnace production. The baseline analysis assumes mineral diesel, while the low-carbon alternative assumes a biofuel blend. It is assumed that the transportation distance is 25 km and uses a diesel articulated HGV (>3.5 - 33t - average laden). Transporting people and construction equipment is insignificant in terms of emissions (<1%), and not accounted for.

Table 2. Life cycle inventory (Mitoulis et al., 2023)

Conversion factors	$kgCO_2e$/unit	Conversion factors	$kgCO_2e$/unit
Concrete C25/30 - CEM 1	0.142/kg	Fibreglass	1.540/kg
Concrete UK C25/30 (25% GGBS)	0.130/kg	FRP	5.000/kg
Steel rebar global average	2.289/kg	Epoxy	5.700/kg
Steel rebar UK 97% recycled EAF	0.835/kg	Rubber	2.660/kg
Stone	0.138/kg	Bearings	1.630/kg
Timber (sawn)	0.587/kg	Water supply	0.344/m3
Portland cement, CEM I	0.860/kg	Diesel (100% mineral) *	3.314/l
Mineral aggregate	0.003/kg	Diesel (biofuel blend) *	3.156/l
Asphalt	0.380/kg	Electricity UK	0.233/kWh
PVC pipe	2.560/kg	Articulated diesel HGV	0.776/km

* Equipment consumption from datasheets (l/h); RT Crane 45T (18.2); Barge B<20m (6.0), JX Piling Rig (7.0) Cat 325 1.5 CY backhoe (23.2), Generic 5HP diesel water pump (0.80, Compressor Kaeser Honda G360 (6.0), Cat D7 Dozer (34.0), Asphalt mixer 16HP (9.2)

Restoration tasks

A three-span river-crossing bridge with shallow foundations is considered for this assessment (Figure 24). Nine scour depths ranging from 1.0 to 5.0m with a step of 0.5m were analysed. Only one pier foundation was scoured. These scenarios lead to a sequence of restoration tasks (R), for various damage states: minor (1, 11, 12, 14, 5), moderate (1, 11, 6, 12, 14, 16, 15, 5), extensive (1, 11, 6, 12, 14, 2, 16, 5, 15), and severe (1, 11, 6, 12, 14, 2, 5, 16, 15, 23). Below, the task ID is followed by the name, weighing factors for damage states (minor/moderate/extensive/severe), and the description of materials and processes.

- *R1*. Armouring countermeasures and flow-altering/cofferdam (0.70/0.80/0.90/1.00) pre-dredging, driving the support piles, bracing, 35 m diameter cofferdam with UBP 305 × 305 × 223 struts, sheet piles, and temporary works, fuel, transportation, and consumable materials.
- *R2*. Temporary support per pier (0.70/0.80/0.90/1.00) two temporary support frames incorporating UC 305 × 158 columns and UB 1016 x 305x 494 beams, and associated platforms, consumables, installation and disassembly, transportation.
- *R5*. Repair cracks and spalling with epoxy and/or concrete (0.50/0.70/0.85/1.00) scaffolding, removal of 50 mm of concrete, new concrete, resurfacing, new parapets, drainage pipes, consumables, on-site activities, transportation, demolition waste.
- *R6*. Re-alignment and/or levelling of the pier (0.50/0.70/0.85/1.00) assembly and disassembly of temporary frames, scaffolding, consumables, transportation.
- *R11*. Erosion protection measures (0.70/0.80/0.90/1.00) excavation, manufacturing and assembly of gabions, steel and stone materials, intervention measures cover both riverbanks, upstream, and downstream for 50 m, transportation.

- *R12.* Rip rap and/or gabions for filling of scour hole and scour protection (0.70/0.80/0.90/1.00) riverbed compaction, rip-rap placement and compaction, transportation of materials and some excavated soil within the site.
- *R14.* Ground improvement per foundation (0.70/0.80/0.90/1.00) excavation around the foundation, installation of a 2 m deep compacted gravel layer, associated materials and consumables, support system as for R2, transportation.
- *R15.* Installation of deep foundation system (1.00/1.00/1.00/1.00) 16 piles of 800 mm diameter and an RC pile cap of 3.5 × 5.5 × 1.5 m with a gross longitudinal rebar ratio of 4%, materials, on-site activities, transportation, temporary frames.
- *R16.* Extension of foundation footing (1.00/1.00/1.00/1.00) footing extension on all sides by 2 m over a depth of 1.5 m, some concrete removal, formwork, materials, transportation, demolition waste.
- *R23.* Demolish/replacement (part) of the bridge (1.00/1.00/1.00/1.00) a pier, and two decks are being replaced, thus R1, R18, 19, and R22 are considered.

According to Table 3, tasks with more temporary works and fewer new materials (R1 and R2) have similar emissions from materials and equipment fuel consumption. Tasks with more new concrete and rebars have higher emissions from materials (R16). The literature shows that around 80% of the emissions are associated with materials extraction and production.
Both assessments assumed the same duration for all restoration tasks, regardless of the materials used. It is assumed that the use of low-carbon materials does not affect task duration and that these materials are available from the same manufacturers as conventional materials. Changes in task duration can impact on-site emissions, but materials and transportation remain constant. Longer construction tasks and associated materials can lead to a 50% increase in emissions due to higher fuel consumption by construction equipment (R1).

Table 3. Environmental impact assessment results

Task	Conventional materials (tCO_2e)	On-site activities (diesel) (tCO_2e)	Trans-portation (diesel) (tCO_2e)	Total (tCO_2e)	Low carbon solution(1) (%)	Influence of duration(2) (%)
R1	16.9	63.6	0.1	80.6	-14.9	±49.8
R2	2.7	4.9	0.1	7.7	-9.6	±30.6
R5	18.3	1.1	1.2	20.6	-17.6	±3.8
R6	3.4	0.7	0.1	4.2	-13.4	±7.5
R11	645.5	29.0	3.5	678.0	-4.6	±1.7
R12	21.7	2.5	0.1	24.3	-1.0	±6.1
R14	29.0	5.0	0.3	34.3	-1.3	±7.0
R15	235.0	113.9	0.4	349.2	-38.3	±10.5
R16	346.5	16.2	0.2	362.9	-57.4	±1.7
R23	1867.1	112.8	5.7	1985.6	-56.7	-3.3

(1) replacement of main construction materials and fuel with low-carbon alternatives
(2) increase/decrease of carbon corresponding to the use of onsite equipment and machinery

Figure 25 presents the carbon associated with each restoration task. The emissions are divided into three categories: materials, on-site activities, and transportation. Materials can account for 21% to 99% of the emissions, with an average of 74% for all activities. On-site activities can represent 2% to 100% of the emissions, while transportation is up to 6%. Some restoration tasks have similar values to those found in the literature (i.e. construction activities contribute to 30% of the total, and transportation is around 4%).

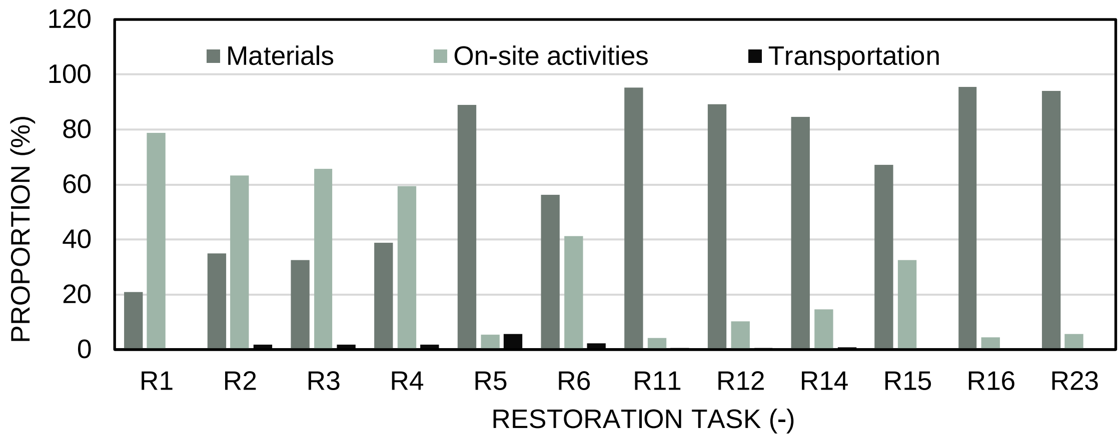


Figure 24 Environmental impact (tCO2e proportion %) due to materials use, on-site procedures, and transportation for each restoration task (Ri).

Using the approach from this assessment, of a recovery of an asset in a post-hazard condition, the designer can set a baseline as well as to investigate various carbon reduction strategies (e.g. low carbon materials, biofuels, etc.).

Industry case studies

Balfour Beatty Rail handled track and minor civil works at London Bridge, including the installation of 158 S&C units and the renewal of approximately 38,000 meters of track (Construction Leadership Council, 2023). An initial baseline, derived from high-level tender data, highlighted gaps, particularly in some work packages. To address these gaps and enhance data accuracy, a workshop with the client, design, and construction teams was conducted, raising awareness of carbon management. A follow-up meeting, chaired by the Project Director, assigned responsibility for data provision. Material data was obtained from outline designs for each work package, and energy usage in the first two years was normalised and applied to the remaining work. The Rail Industry Carbon Tool was employed to calculate the carbon baseline, ensuring transparency and traceability. Effective baseline planning and early engagement from key stakeholders are essential for precise baseline calculations and successful carbon management throughout the project.

WSP-Parsons Brinckerhoff Rail and Atkins acted as the Lead Design Organisation (LDO) for Network Rail's electrification programme extending from London to Oxford, Bristol, and South Wales (Construction Leadership Council, 2023). A carbon reduction study was carried out at the Detailed Design stage, focusing on embodied carbon in construction materials for Route Sections under LDO responsibility, while transportation and construction emissions were calculated by other contractors. Carbon hotspots were identified using the RSSB Tool, leading to opportunities for reduction. These included reducing material quantity through pile depth reductions and introducing a thinner OLE mast option to decrease steel and carbon emissions. Material specification changes included using concrete mixes with higher levels of GGBS to lower carbon, though opportunities for reclaimed or low-carbon steel were limited due to prior procurement decisions.

Allies and Morrison Architects, in collaboration with Arup, developed a masterplan for Madinat Al Irfan, a mixed-use district near Muscat International Airport, Oman, aiming to set benchmarks for sustainable urban development and carbon reduction (Construction Leadership Council, 2023). The masterplan included a study that quantified emissions for the base case, identifying major sources such as transport, energy, and potable water supply. Performance targets were established through workshops with the client and design team, focusing on significant improvements beyond baseline conditions. Carbon emissions were not stated directly but were estimated using proxies to calculate reductions. The goal was to lower per-kilometre travel emissions by promoting walking and public transport over car use. Results showed that capital carbon emissions for the building and infrastructure were comparable between the Irfan Case and the Base Case, while forecast carbon emissions for Madinat Al Irfan over 20 years were 40% lower than the Base Case. Additionally, forecast costs for the Irfan development over 20 years were reduced by 44% compared to the baseline.

Summary

In this learning activity, the selection of databases, life-cycle inventories, and assessment steps essential for evaluating upfront carbon emissions in both conventional and sustainable solutions was explored. Selected industry case studies were examined to understand practical approaches to infrastructure carbon management, providing insights into how these methodologies could be applied effectively in real-world scenarios. The activity largely referred to the approaches adopted in EN17472:2022 ‘Sustainability of construction works’, recognised as the most relevant European Norm for infrastructure projects. Simplified procedures to evaluate embodied carbon at the design stage were covered.

The simplified assessment case study involved a benchmark transport asset, specifically a typical river-crossing 3-span bridge with shallow foundations, assessed under nine flood scenarios. A baseline analysis and a feasibility study for adopting low-carbon solutions was carried out. Three industry case studies highlighted effective carbon management: Balfour Beatty Rail's track renewal at London Bridge involved stakeholder workshops to address baseline data gaps and employed the Rail Industry Carbon Tool for accurate carbon calculations; WSP-Parsons Brinckerhoff Rail and Atkins reduced carbon in Network Rail's electrification programme by identifying hotspots and adjusting material specifications; Allies and Morrison Architects' masterplan for Madinat Al Irfan in Oman set sustainability benchmarks, achieving a 40% reduction in forecast carbon emissions and a 44% cost reduction over 20 years compared to the baseline.

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