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

Massive Open Online Course:

Resilience, Sustainability & Digitalisation in Critical Infrastructure

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Lecture 4

Massive Open Online Course

Resilience, Sustainability & Digitalisation in Critical Infrastructure

Sustainability assessments

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Lecture 4 Outcomes

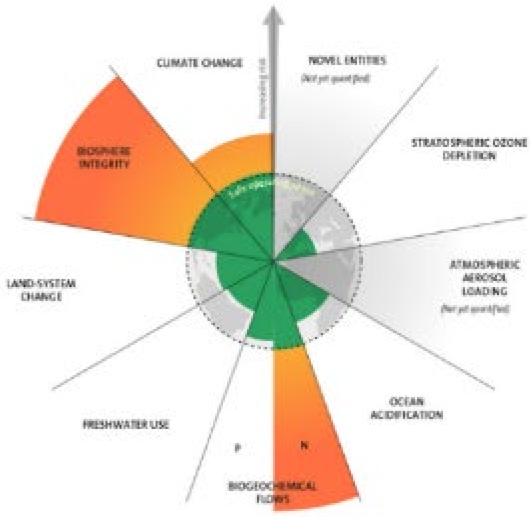
- Define **sustainability** in the context of infrastructure projects and explore sustainable and **circular** design principles in minimising resource consumption and waste generation.
- Understand the purpose, phases, parameters, and limitations of **life-cycle assessments** (LCA) in assessing the environmental impact of products and projects.
- Undertake **whole-life carbon emissions** assessments for infrastructure assets and networks, and systems, adopt low-carbon solutions and manage carbon at all work stages.

ACTIVITY 1: Introduction to sustainability and circularity

- Definition of sustainability in the context of infrastructure projects.
- Exploring the importance of sustainable design principles in minimising resource consumption and waste generation.
- Understanding how circularity contributes to the sustainability of infrastructure projects

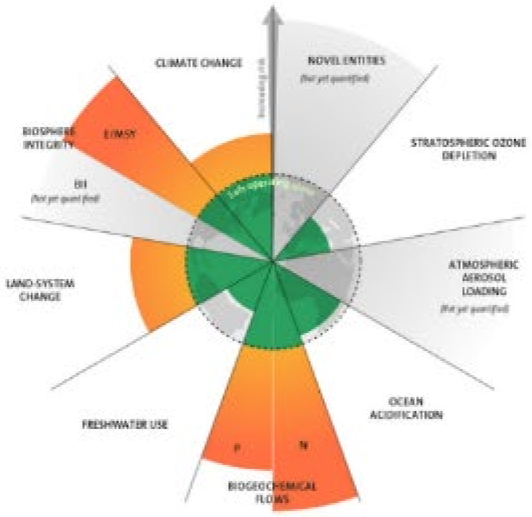
Planetary boundaries

2009



7 boundaries assessed,
3 crossed

2015



7 boundaries assessed,
4 crossed

2023

9 boundaries assessed,
6 crossed

Azote for Stockholm Resilience Centre, Stockholm University. Based on Richardson et al. 2023, Steffen et al. 2015, and Rockström et al. 2009

What is sustainability?

Sustainability

the quality of being able to continue over a period of time:

- the long-term sustainability of the community

the quality of causing little or no damage to the environment and therefore able to continue for a long time:

- the company's commitment to environmental sustainability

Brundtland Report ‘Our common future’ (1987)

“Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs.”

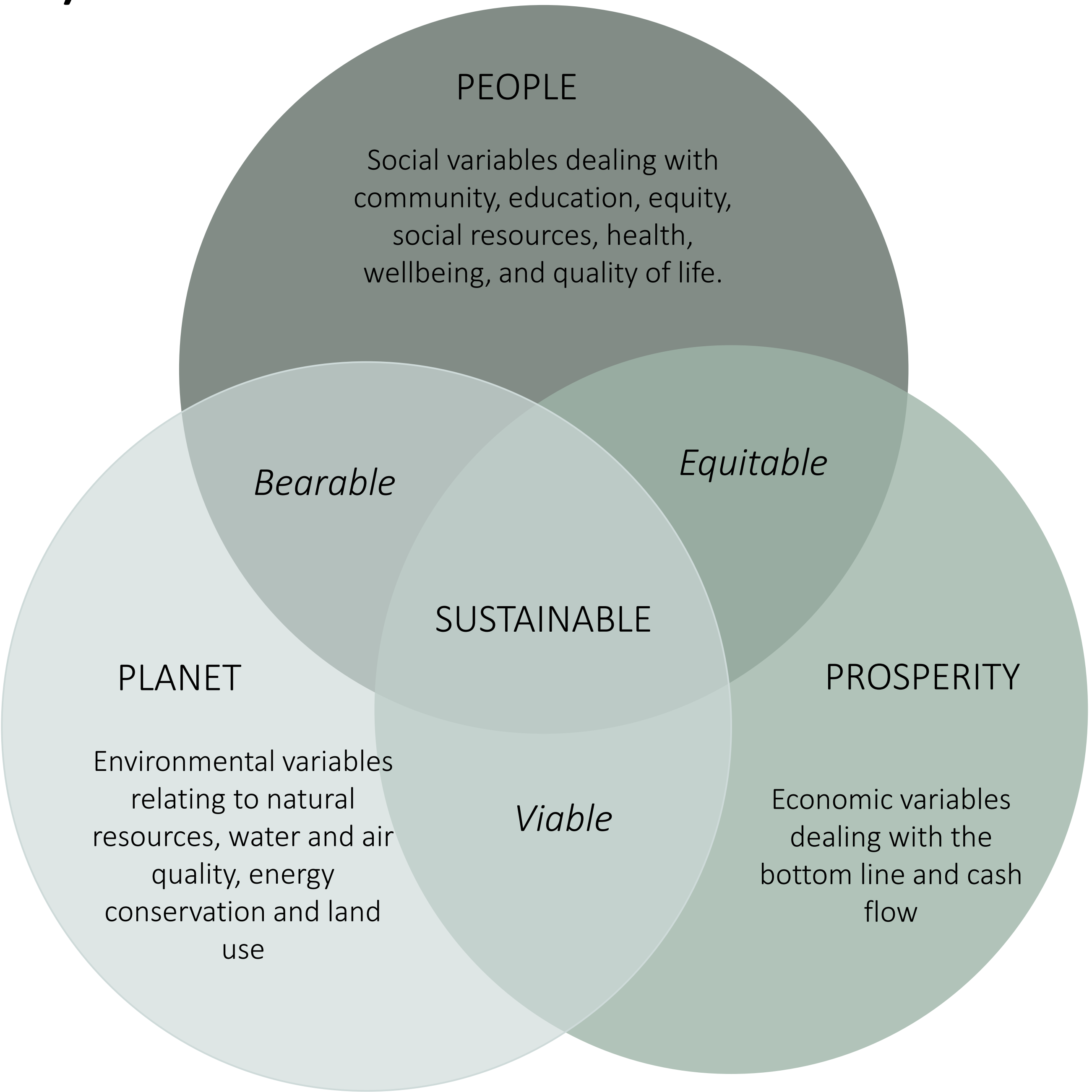
Brundtland Report 'Our common future' (1987)

1. re-examine the critical issues of environment and development

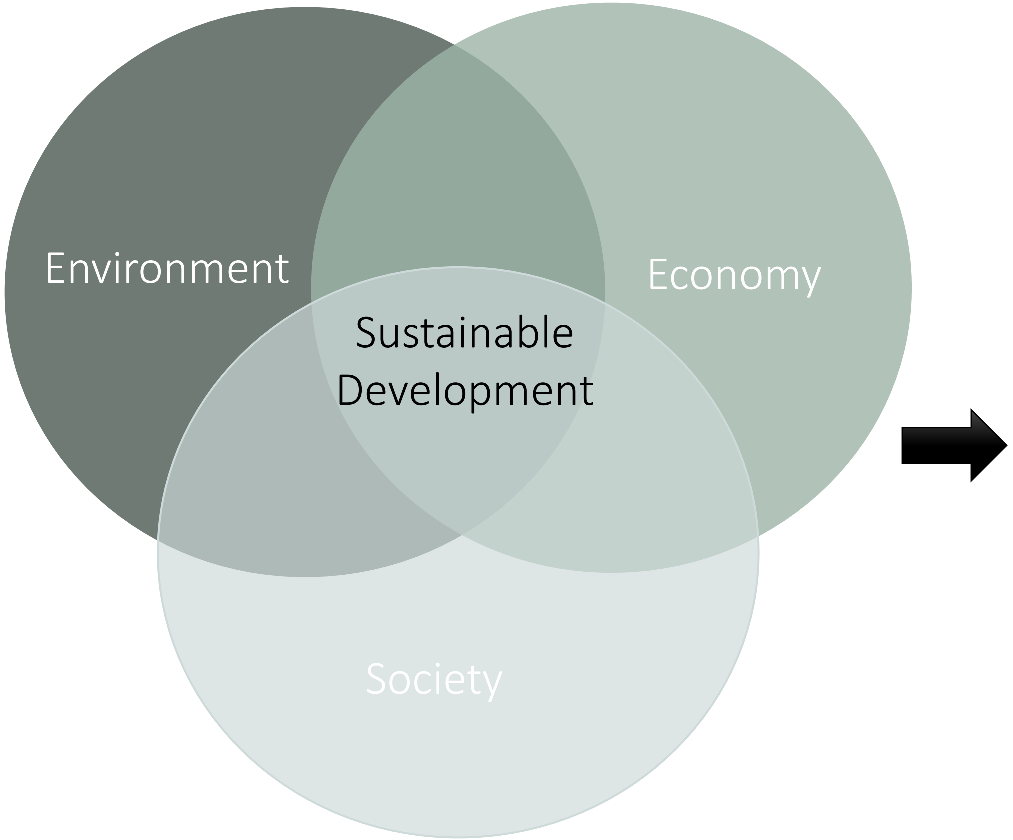
2. strengthen international cooperation on environment and development … can break out of existing patterns and influence policies ….

3. and raise the level of understanding and commitment to action …

Measuring impact? (1987)

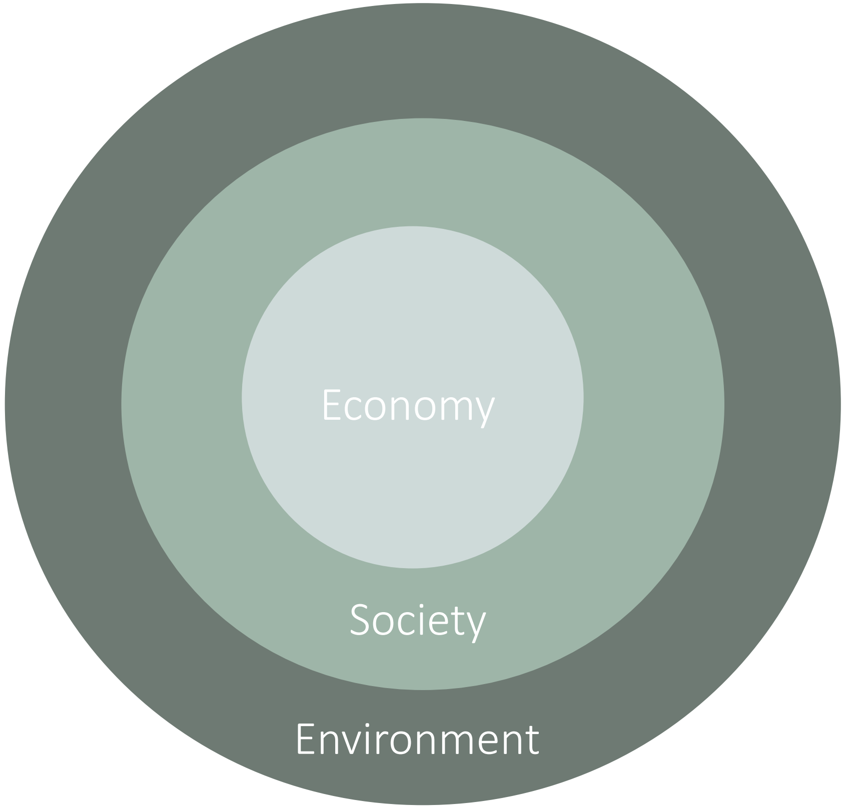


Sustainability models



'Weak' sustainability

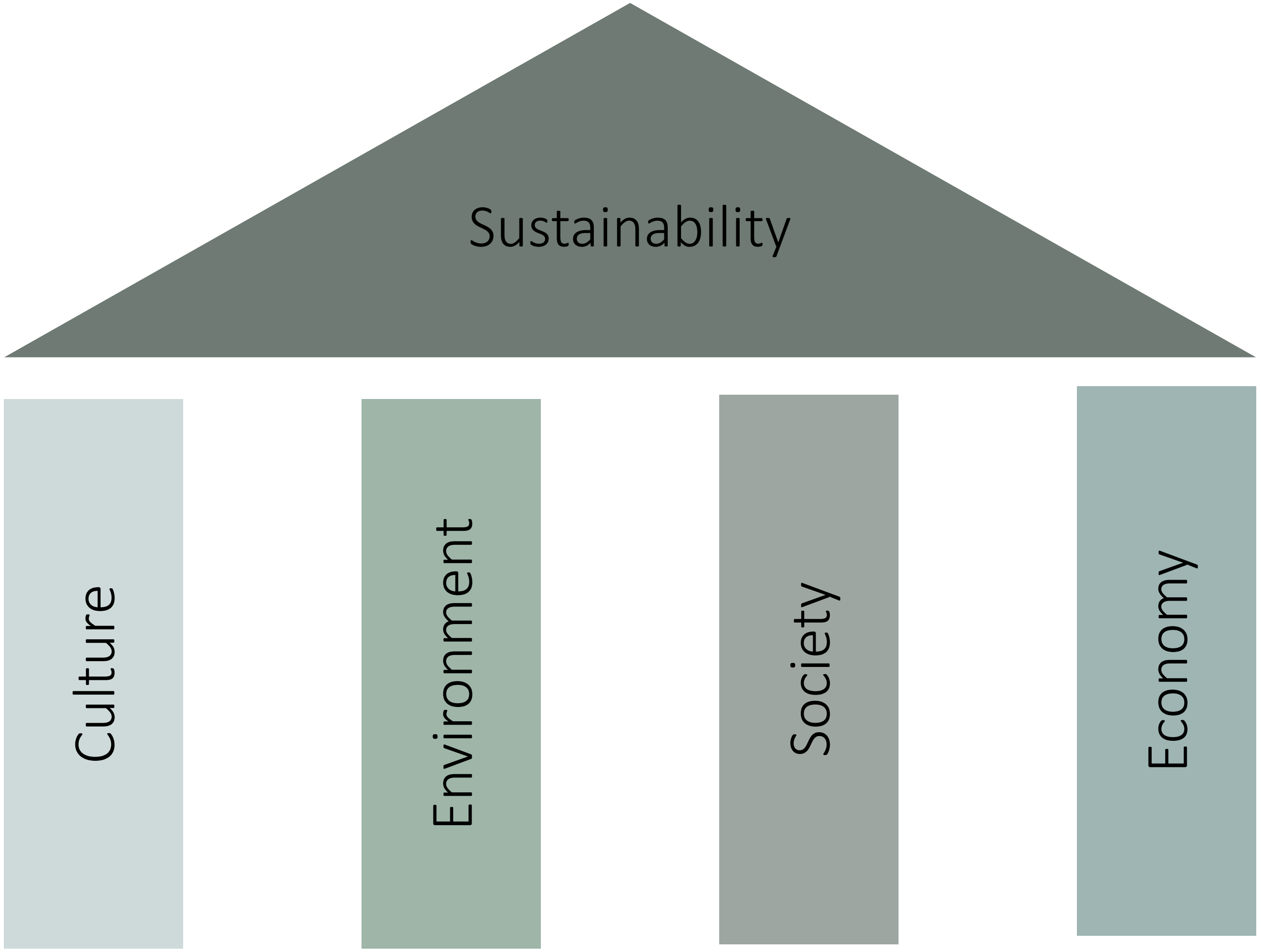
(Brundtland Report, 1987)



'Strong' sustainability

(Giddings, 2002)

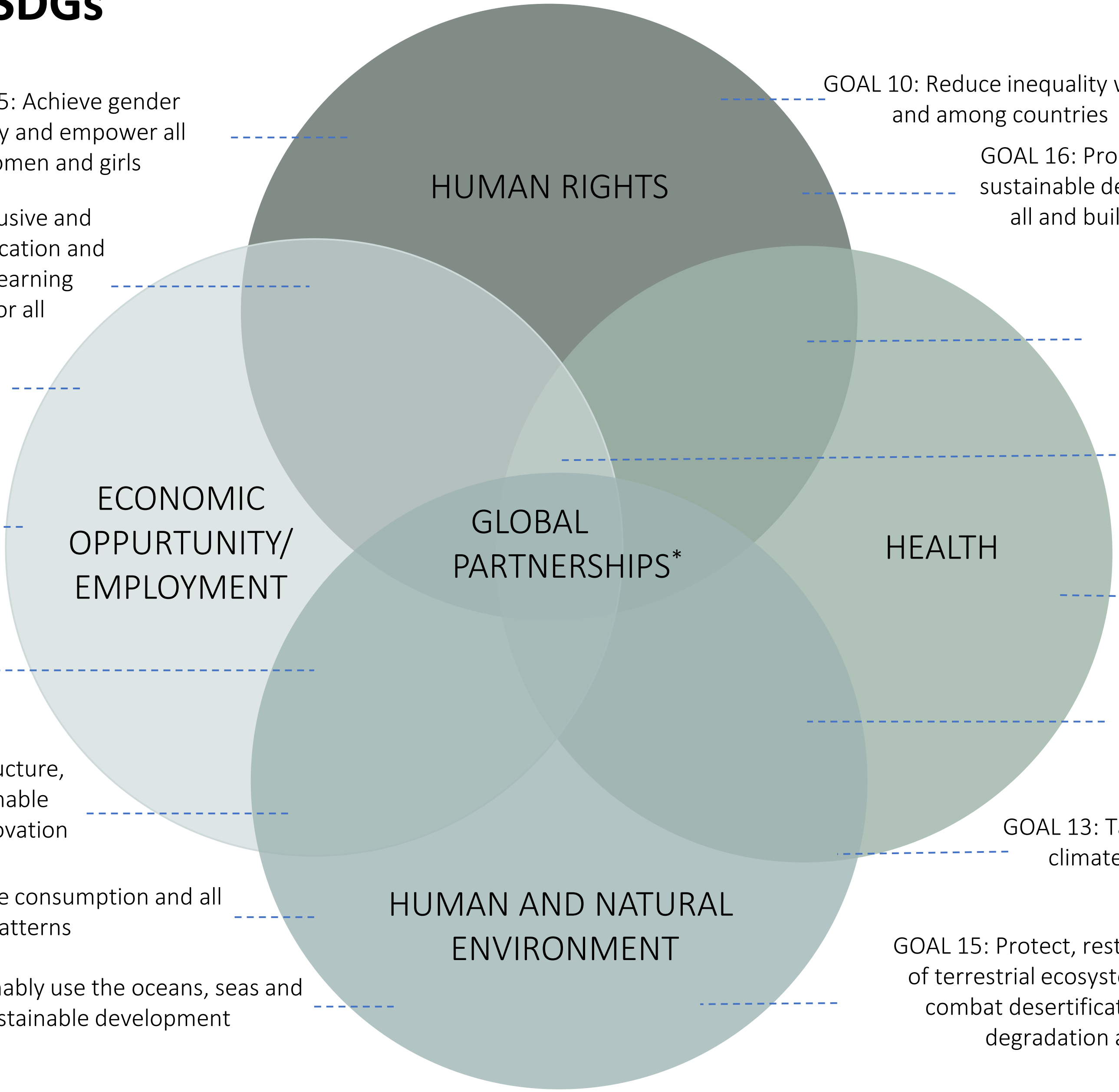
Pillars



UN Sustainable Development Goals

https://sdgs.un.org/goals

Breaking down the UN SDGs



GOAL 5: Achieve gender equality and empower all women and girls

GOAL 4: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all

GOAL 1: End poverty in all its forms everywhere

GOAL 8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all

GOAL 7: Ensure access to affordable, sustainable and modern energy for all

GOAL 9: Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation

GOAL 12: Ensure sustainable consumption and all production patterns

GOAL 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development

GOAL 10: Reduce inequality within and among countries

GOAL 16: Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels

GOAL 6: Ensure availability and sustainable management of water and sanitation for all

GOAL 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture

GOAL 3: Ensure healthy lives and promote wellbeing for all at all ages

GOAL 11: Make cities and human settlements inclusive, safe, resilient and sustainable

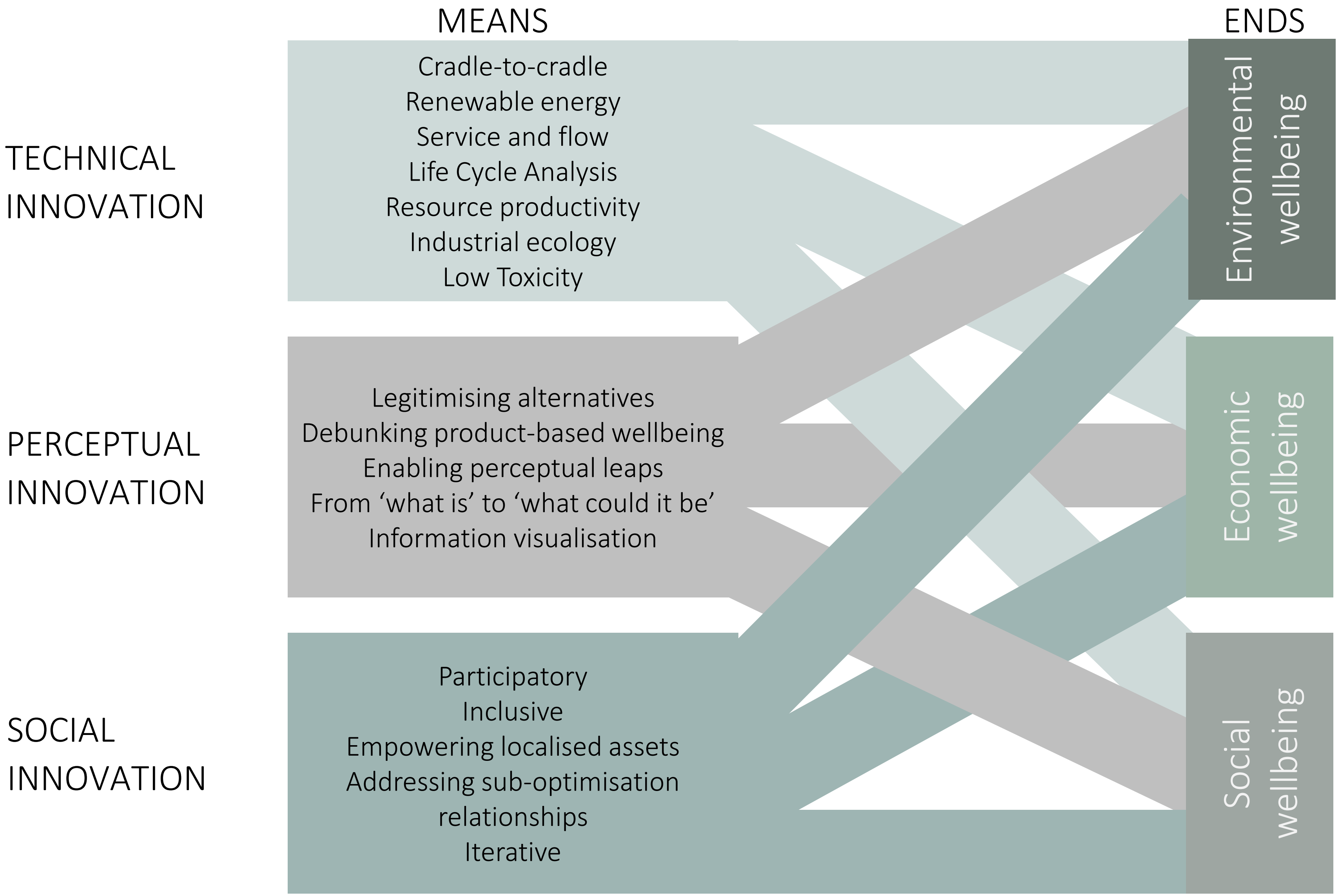
GOAL 13: Take urgent action to combat climate change and its impacts

GOAL 15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably mange forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss

*GOAL 17: Strengthen the means of implementation and revitalise the global partnership for sustainable development

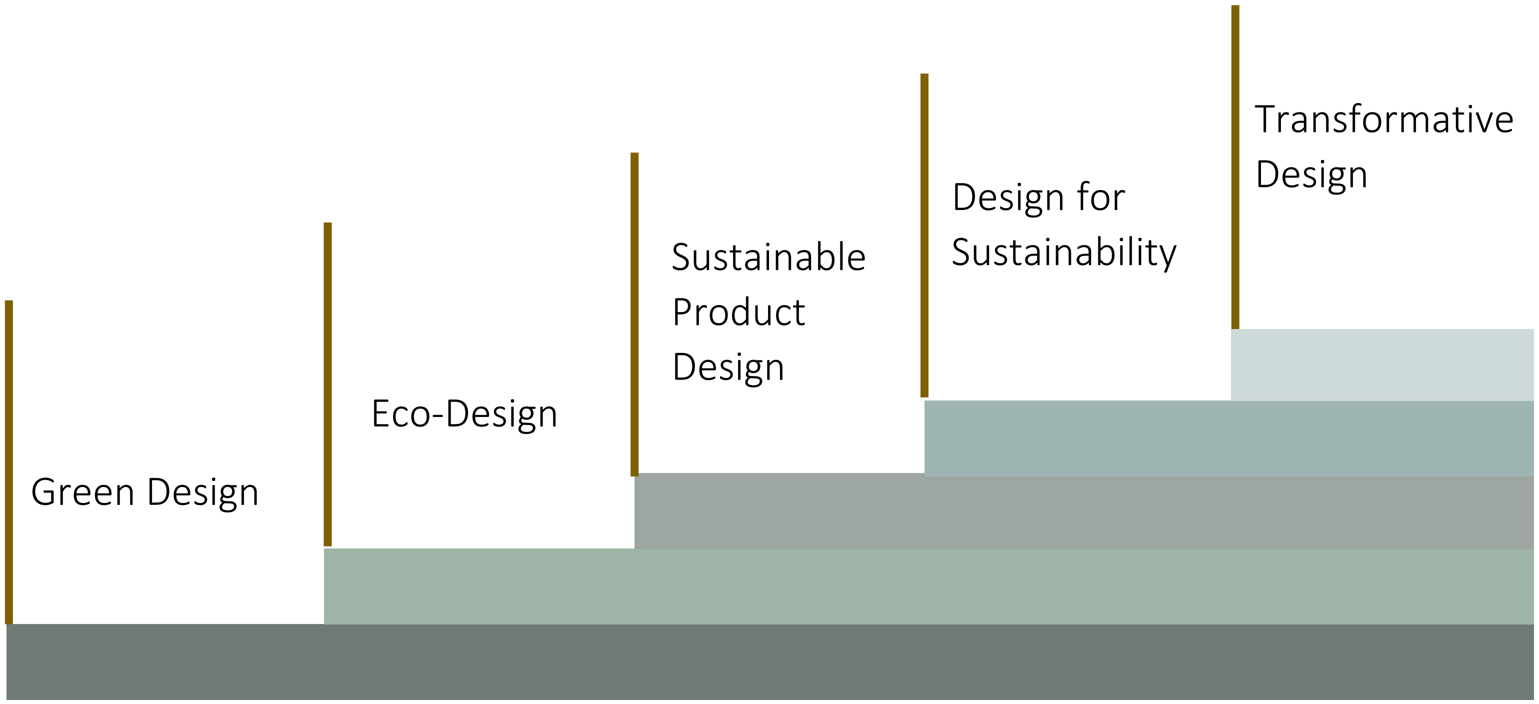
Adapted from PYXERA Global (2015)

Unleashing sustainability



Adapted from scad.edu

Sustainable product design



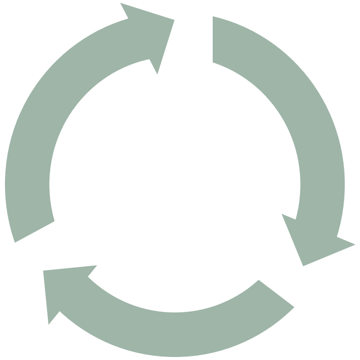
Beyond business as usual

less harm

Beyond business as usual

less harm

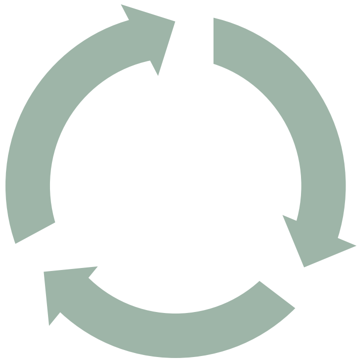
zero waste



Beyond business as usual

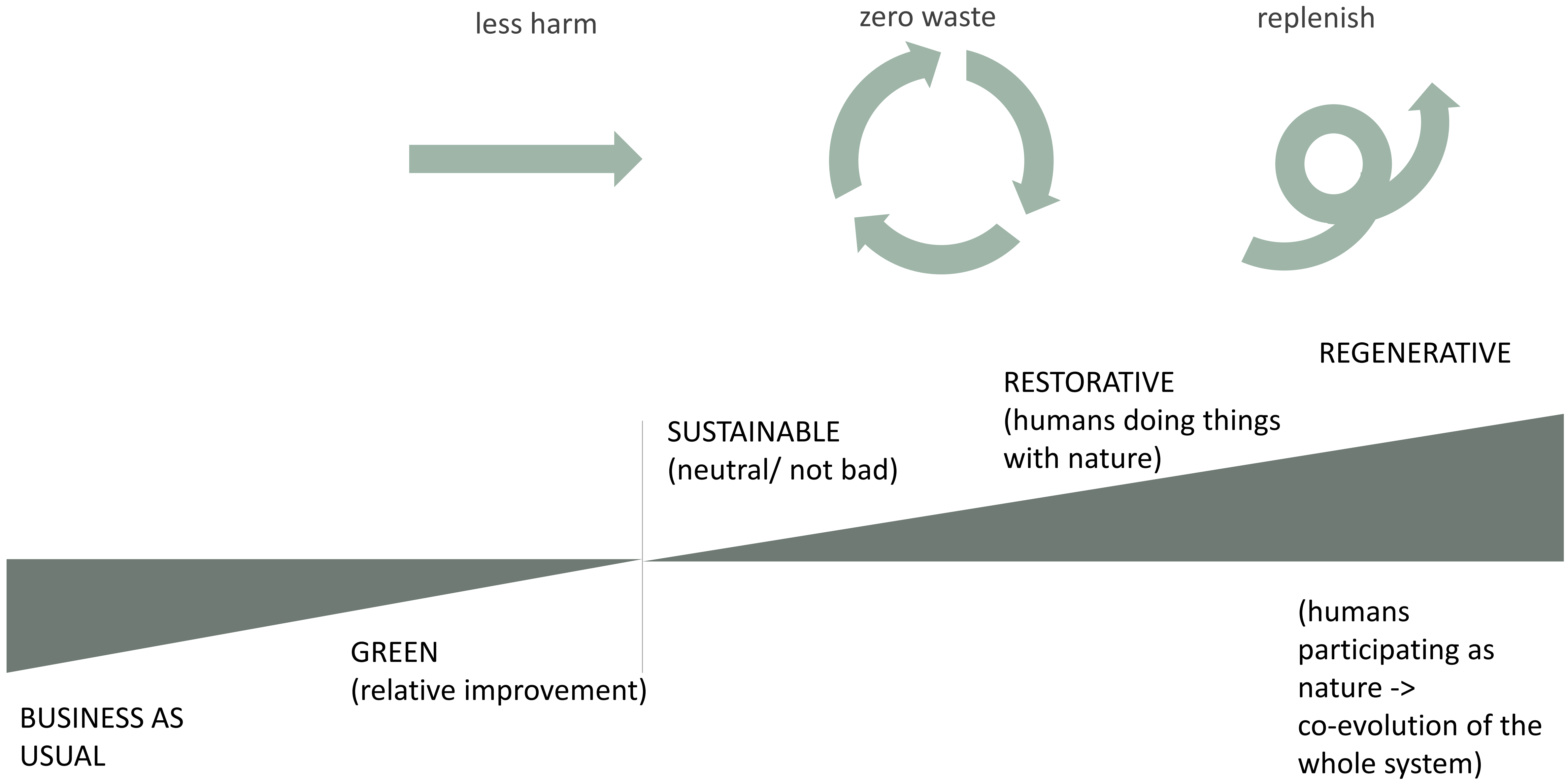
less harm

zero waste

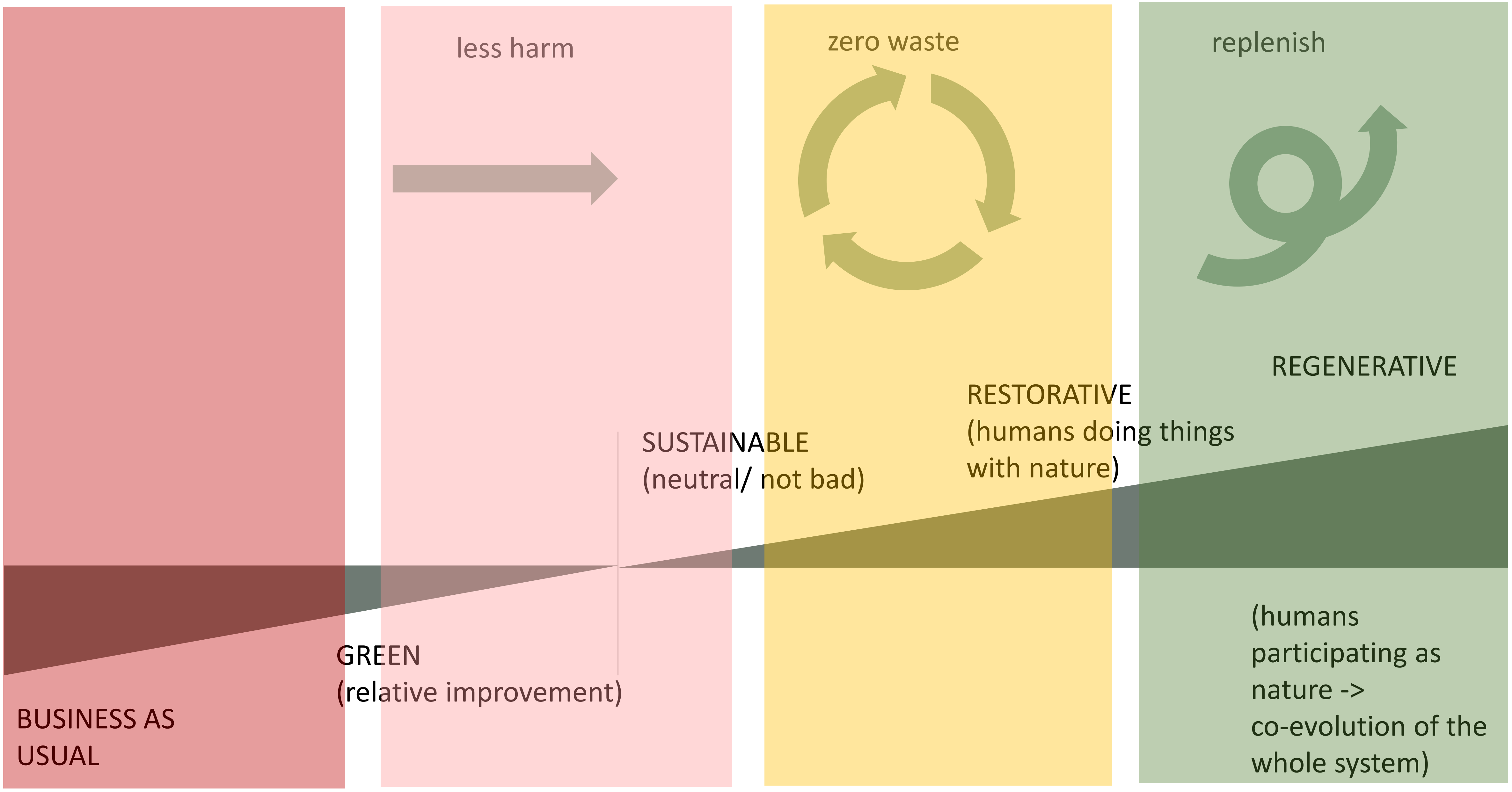


replenish

Beyond business as usual



Beyond business as usual

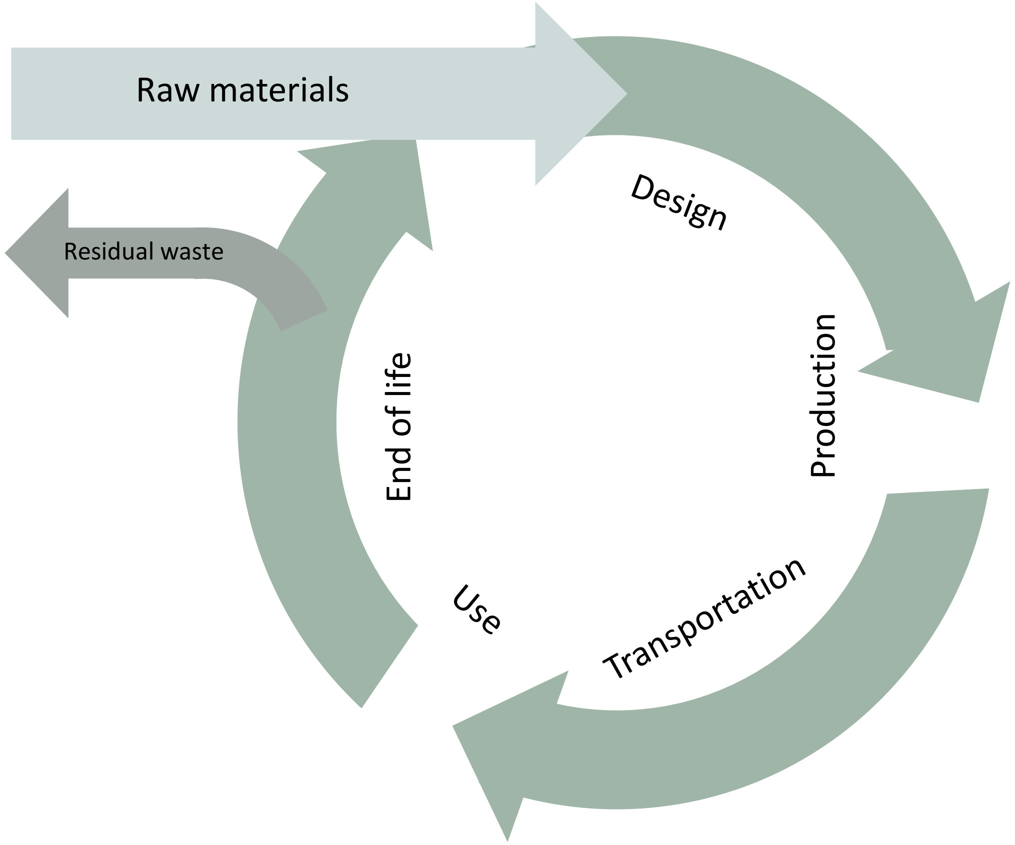


Linear model

- Since the industrial revolution, global economies have developed a "take-make-consume and dispose" growth model.
- This linear model assumes that resources are plentiful, easily accessible and inexpensive to dispose of.
- The linear model is not sustainable!
- Finite and often scarce valuable materials are lost due to waste disposal.
- Increasing demand for those resources, puts an increasing strain on both the environment as well as on the economy.

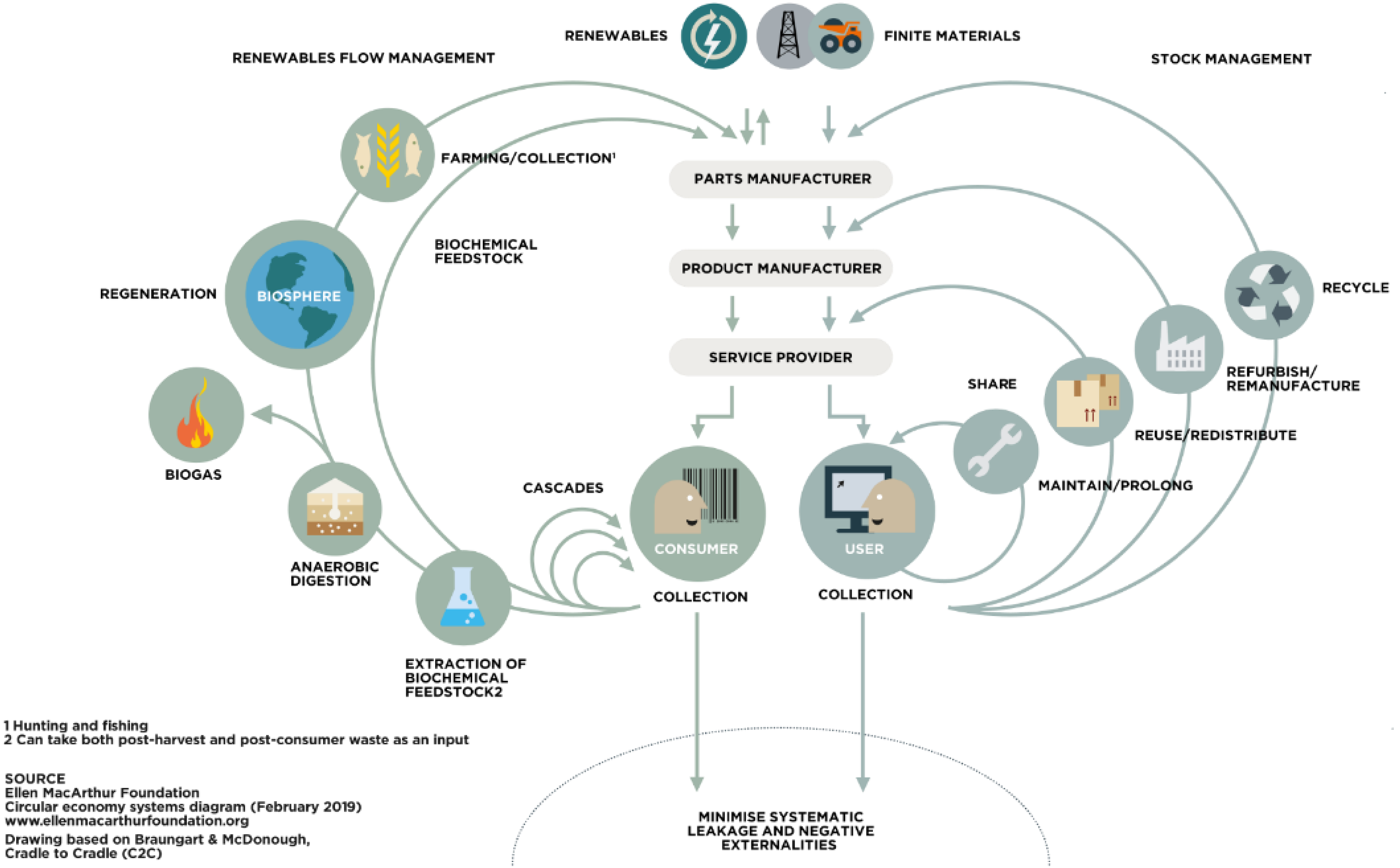
Circular model

Thus, it is essential to move to a different economic model (**Circular Economy**), which is **“restorative by intention, and aims to decouple economic growth from the use of natural resources and ecosystems by using those resources more effectively and eliminating waste”.**



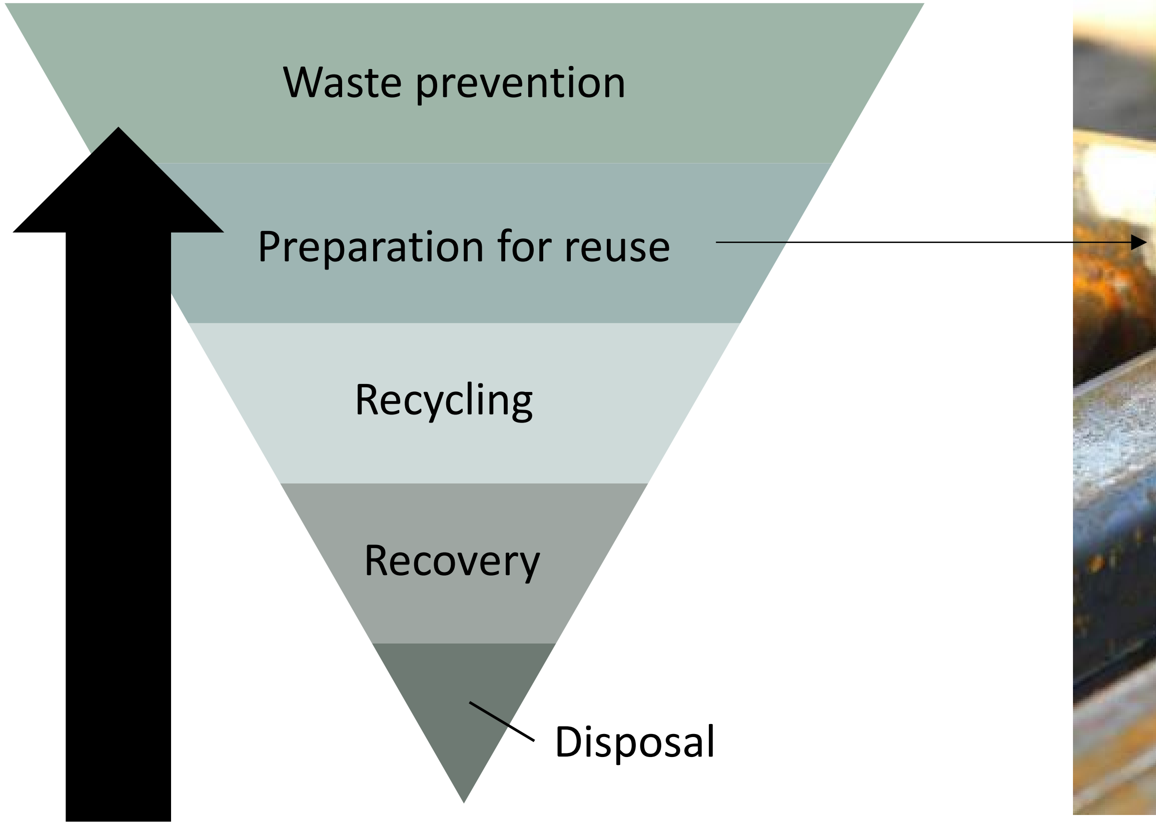
Adapted from COM(2014) 398

Circular model



https://www.ellenmacarthurfoundation.org/circular-economy-diagram

EU and UK waste management hierarchy



Lifecycle of infrastructure

<table>
<tr><td>Need</td><td colspan="4">Optioneering</td><td colspan="2">Design</td><td colspan="2">Delivery</td><td colspan="2">Operation</td><td>Purpose & performance review</td></tr>
<tr><td>Strategy</td><td>Prepa-ration & brief</td><td colspan="2">Concept</td><td>Defini-tion</td><td colspan="2">Technical design</td><td>Manufacture, construct & commission</td><td colspan="2">Hand-over & closure</td><td>Use</td><td>End of life</td></tr>
<tr><td>Strategy</td><td colspan="2">Preparation and briefing</td><td colspan="2">Concept design</td><td>Technical design</td><td>Spatial coordi-nation</td><td>Manufacture & construction</td><td colspan="2">Hand-over</td><td>Use</td><td>End of life</td></tr>
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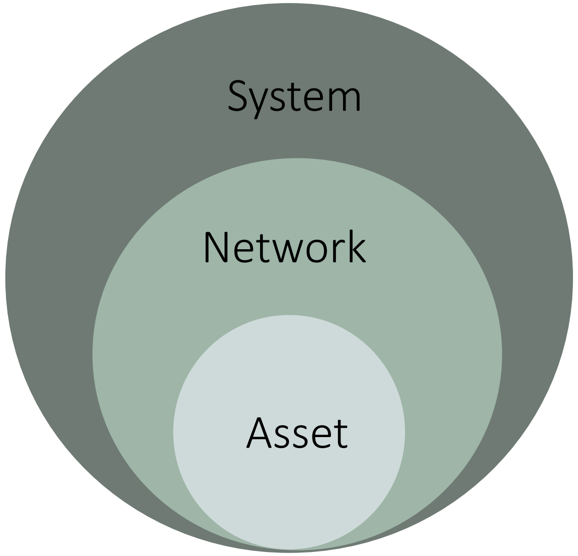
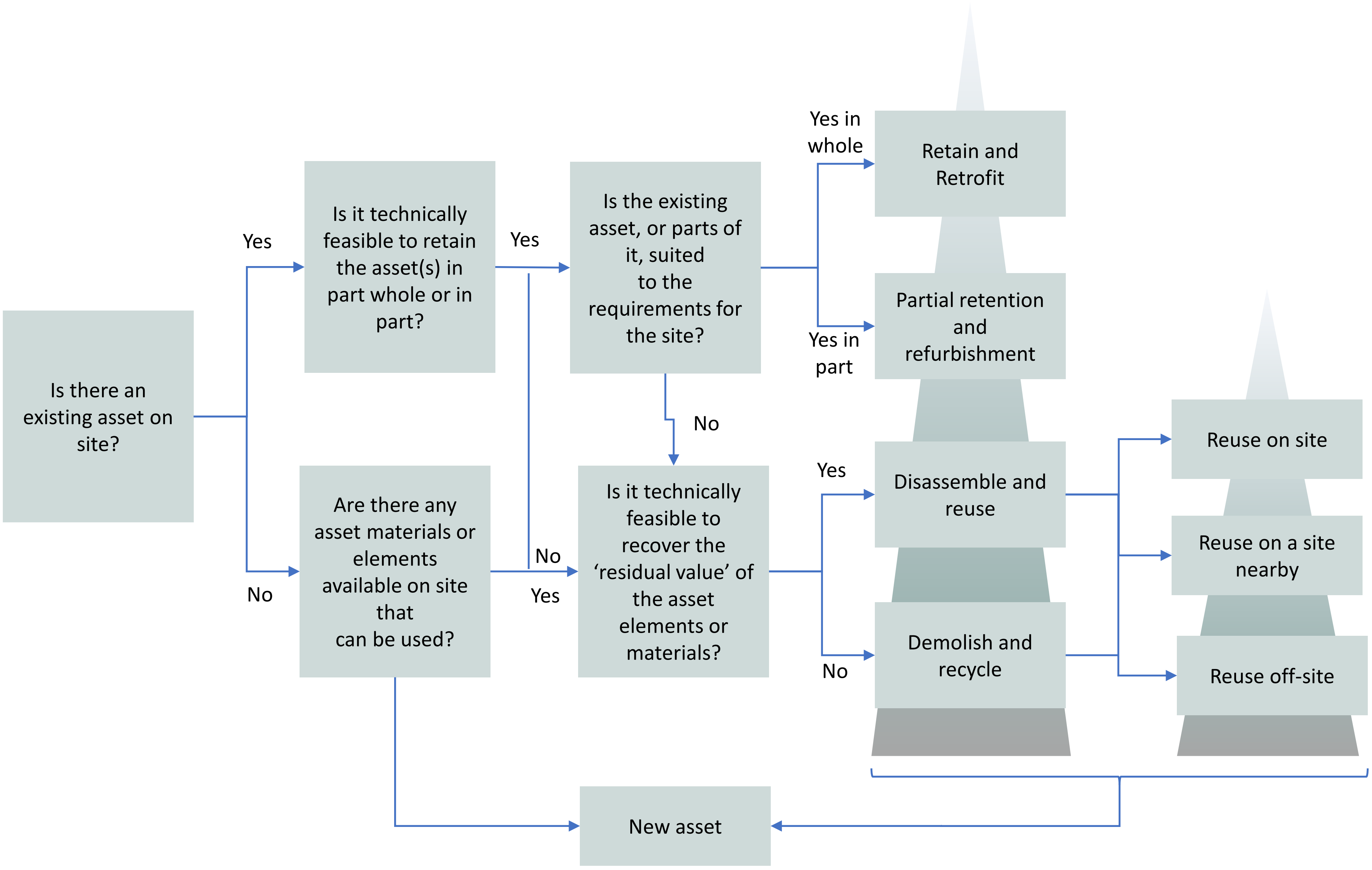
PAS2080:2023	Carbon management in buildings and infrastructure
BS 8536:2022	Design, manufacture and construction for operability
RIBA Plan of Work	Model for the design and construction process of buildings



Sustainability enhancements

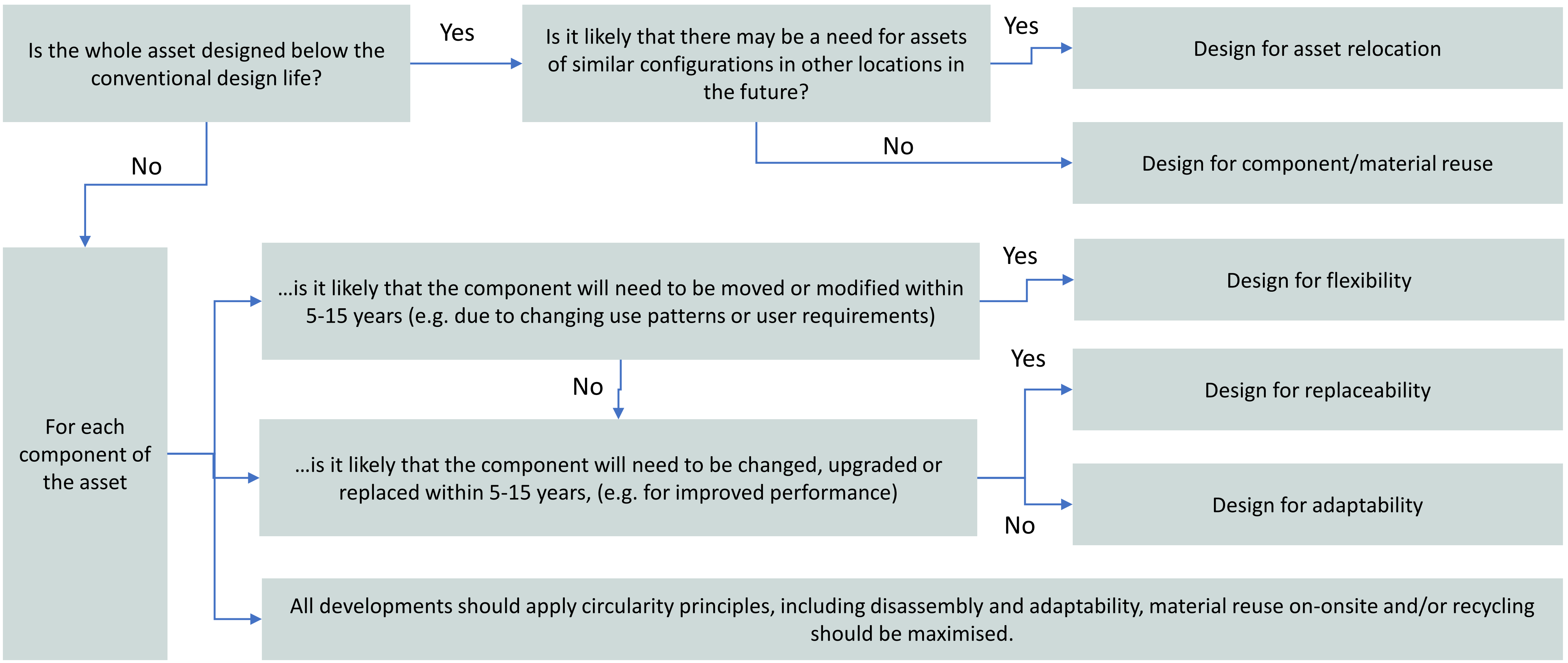
Site selection Retrofit/strengthen/avoid new builds Adaptive re-use	Need
Materials selection Structural system Meeting targets Benchmarking Holistic design	Optioneering
Sustainability targets Specification Optimisation	Design

Decision tree for design approaches for existing assets



Modified from London Plan Guidance – Circular Economy Statements (2022)

Design tree for design approaches for new assets



Modified from London Plan Guidance – Circular Economy Statements (2022)

SUMMARY

- Definition of sustainability in the context of infrastructure projects.
- Exploring the importance of sustainable design principles in minimising resource consumption and waste generation.
- Understanding how circularity contributes to the sustainability of infrastructure projects

ACTIVITY 2: Life-cycle assessments

- Definition and purpose of LCA in assessing the environmental impact of products and projects.
- Goal and scope definition, inventory analysis, impact assessment, and interpretation.
- Overview of available LCA software and tools for streamlining assessments.

Life cycle assessment (LCA)

"Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle"

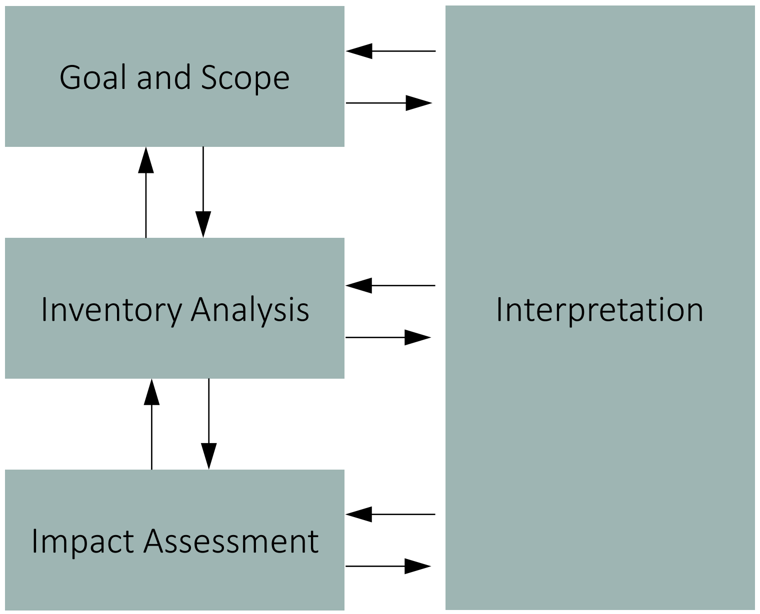
- Only environmental considerations addressed
- Economic, social, and other aspects could be considered with other tools
- Iterative process where each phase uses results of other phases
- Process split into life cycle stages/modules and LCA phases/steps
- Stages are portions of the product life cycle and phases are the portions of the LCA process
- Data collected on inputs and outputs of the system
- Associated environmental and resource impacts of those inputs and outputs

ISO 14040 Environmental management. Life cycle assessment. Principles and framework

Phases versus stages

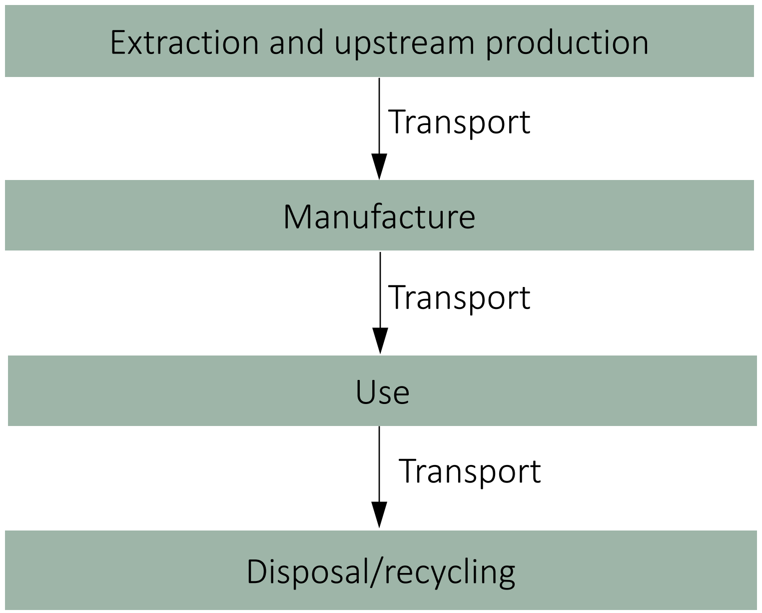
Phases

Portions of LCA procedure



Stages

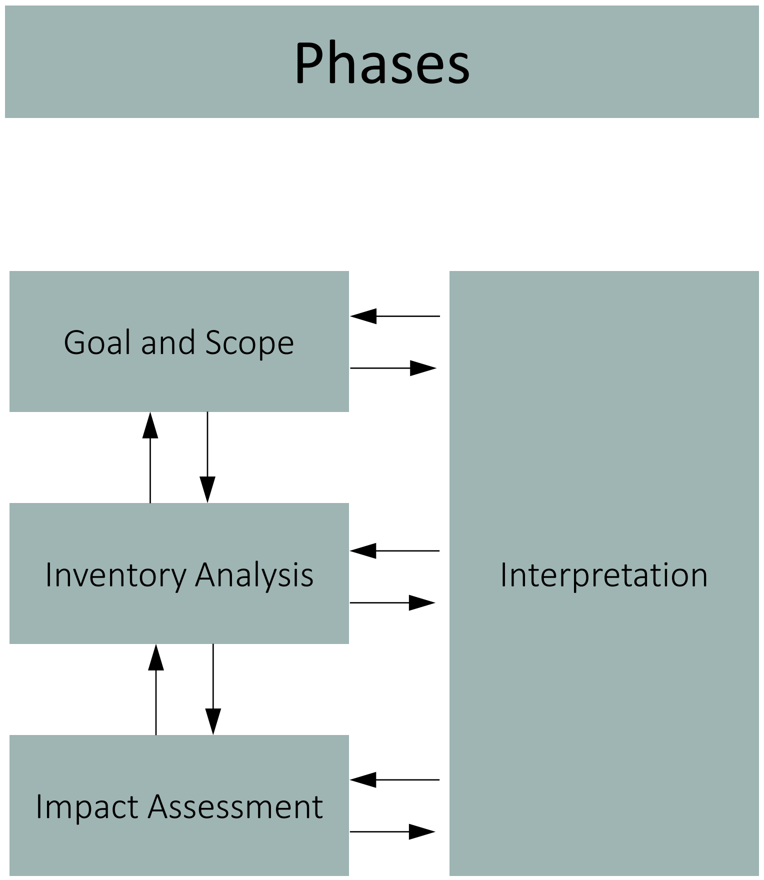
Sections of product life cycle



Note: This is a general diagram of stages, and some products or processes may have more or less stages than those shown here

ISO 14040 Environmental management. Life cycle assessment. Principles and framework

Questions in LCA



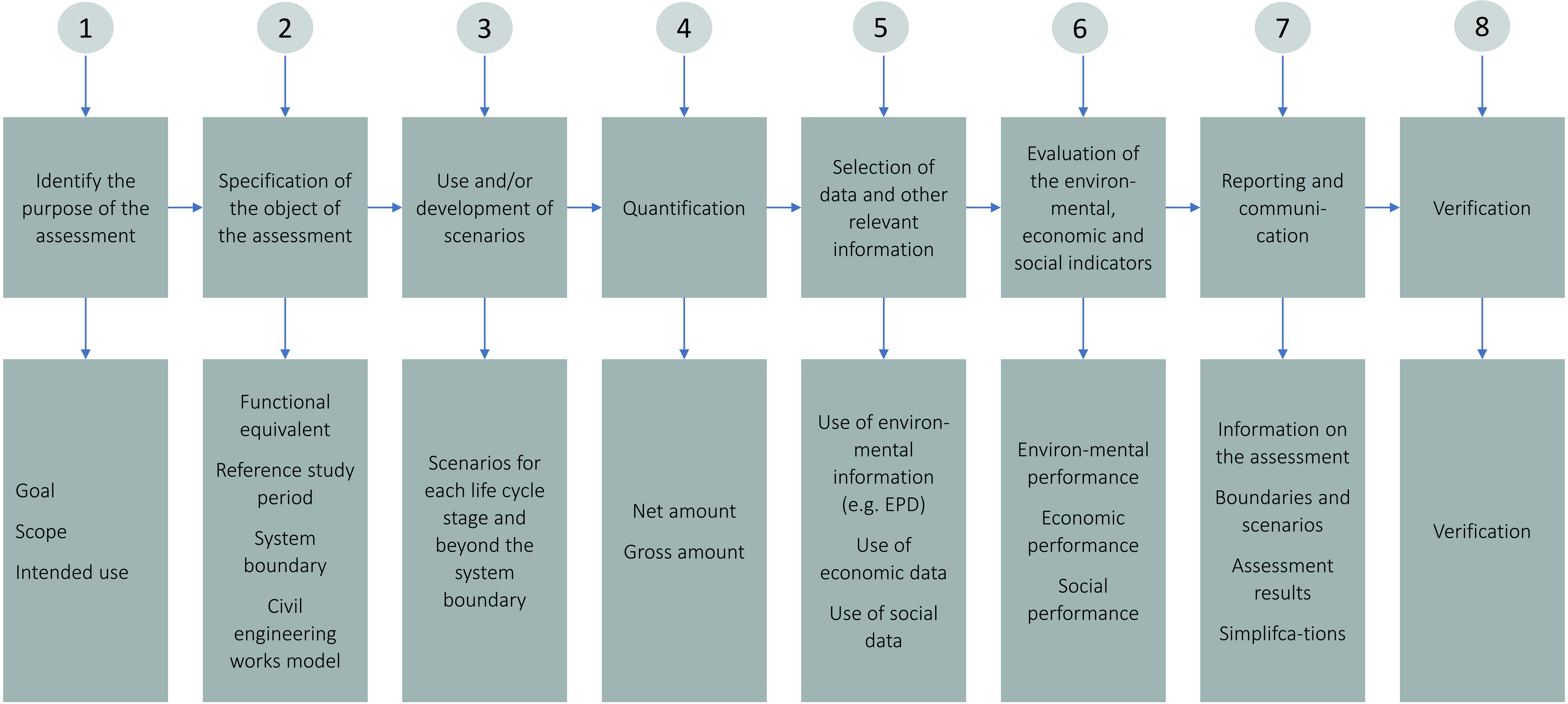
1. Goal: what do we want to know? (**Attributional/Consequential**)
2. Scope: What is the product/service (in quantitative terms)? (**Functional Unit**)
3. What emissions to and resources from the environment are needed? (**Life-Cycle Inventory**)
4. How do these processes affect the environment? (**Impact Assessment**)

ISO 14040 Environmental management. Life cycle assessment. Principles and framework

European Norms

- **EN 17472** - Sustainability of construction works - Sustainability assessment of civil engineering works - Calculation methods
- **EN 15643** - Sustainability of construction works. Sustainability assessment of buildings and civil engineering works
- **EN 15978** - Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method
- **EN 15804** - Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products

Steps of the assessment process

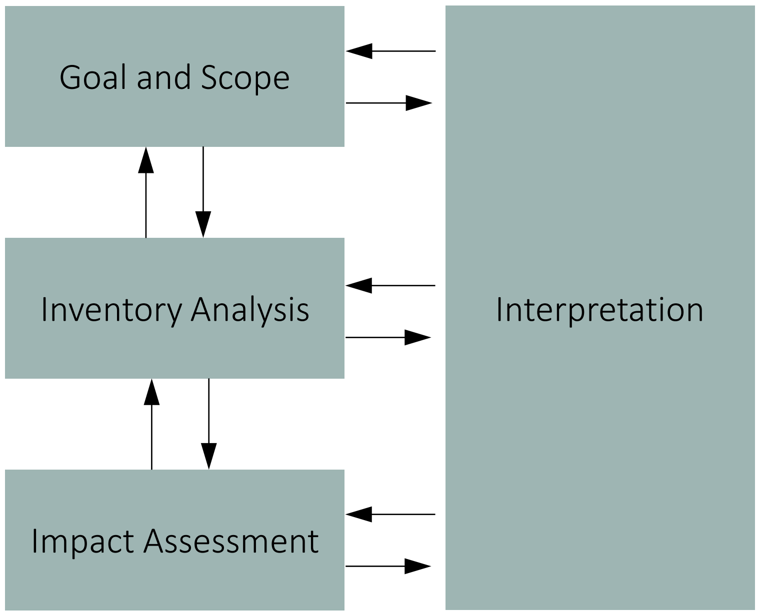


From EN17472 Sustainability of construction works. Sustainability assessment of civil engineering works. Calculation methods.

Phases versus stages

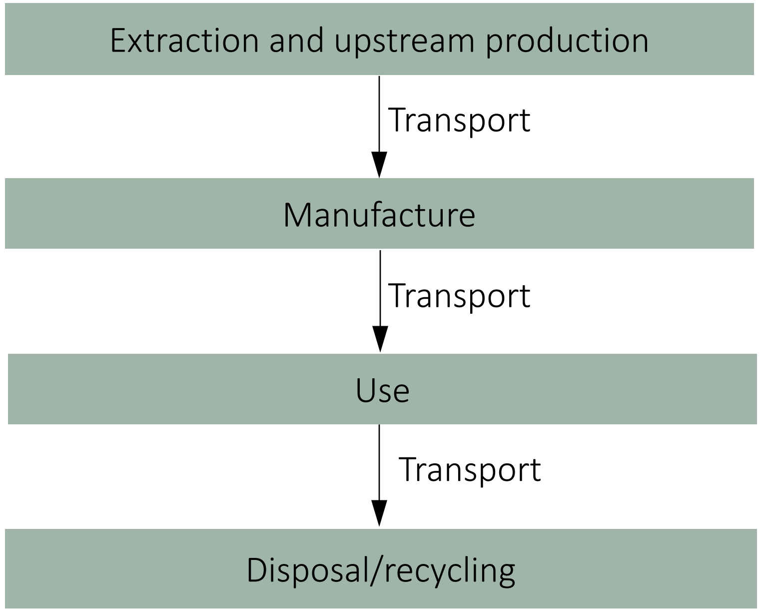
Phases

Portions of LCA procedure



Stages

Sections of product life cycle



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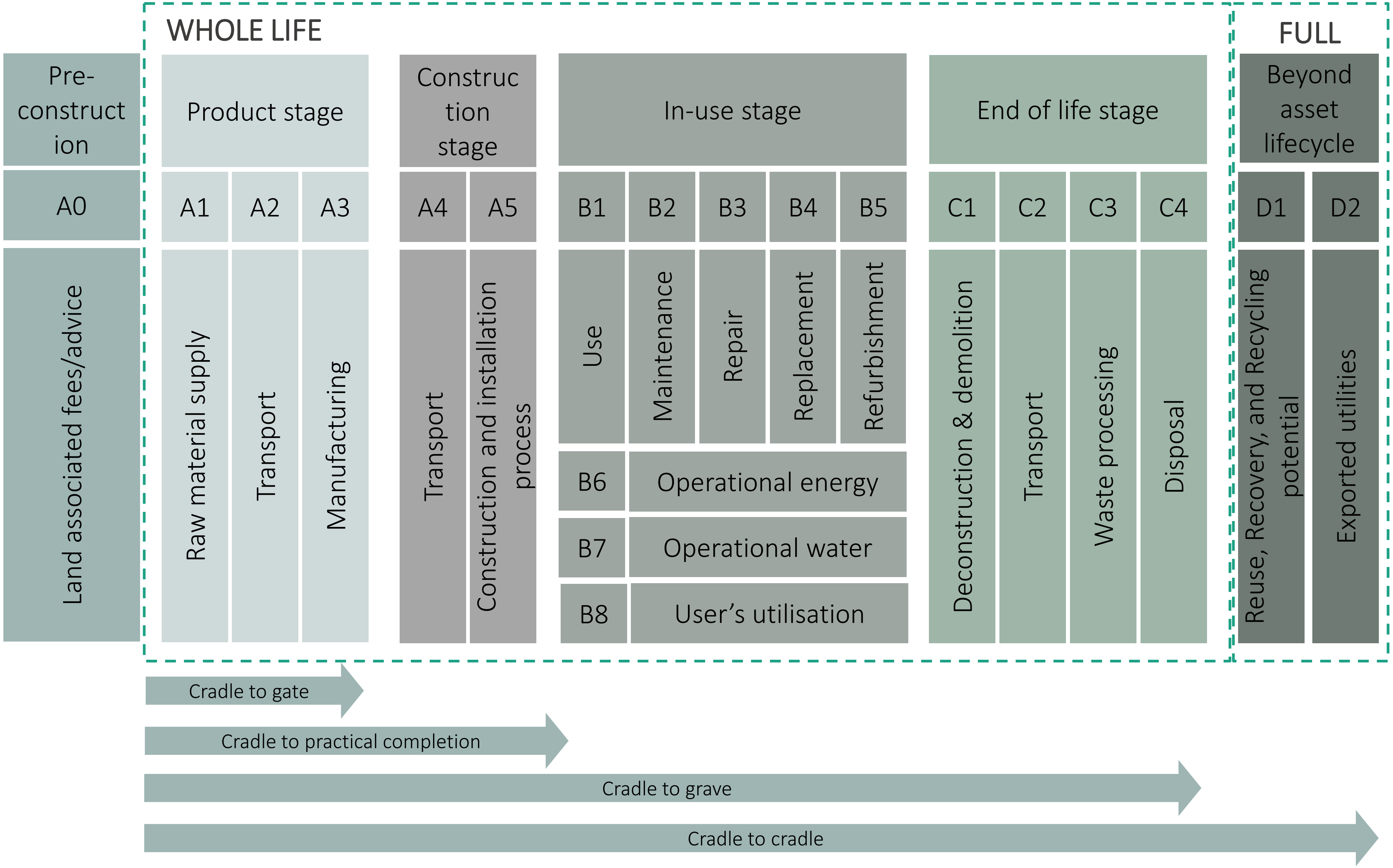
Civil engineering works assessment system boundary



From EN17472 Sustainability of construction works. Sustainability assessment of civil engineering works. Calculation methods.

Functional unit

- **Quantifies** the **function** of the product/service/system under
- **Reference**: must be the same for all alternatives
- Basis for the LCA study

→ System reference unit, lifespan, system performance

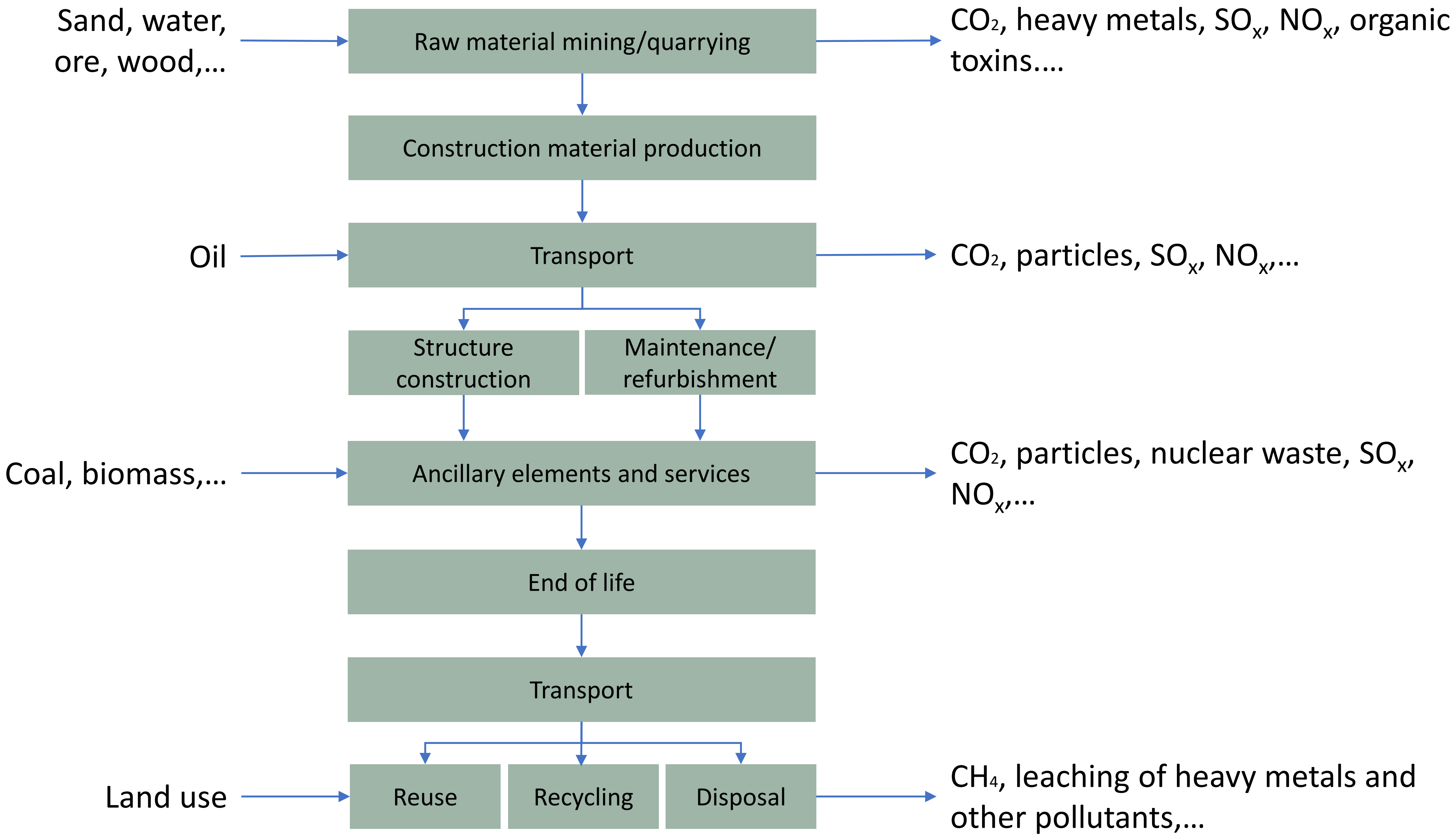
Example paint system: m^2 surface protected for 10 years

ISO 14040 Environmental management. Life cycle assessment. Principles and framework

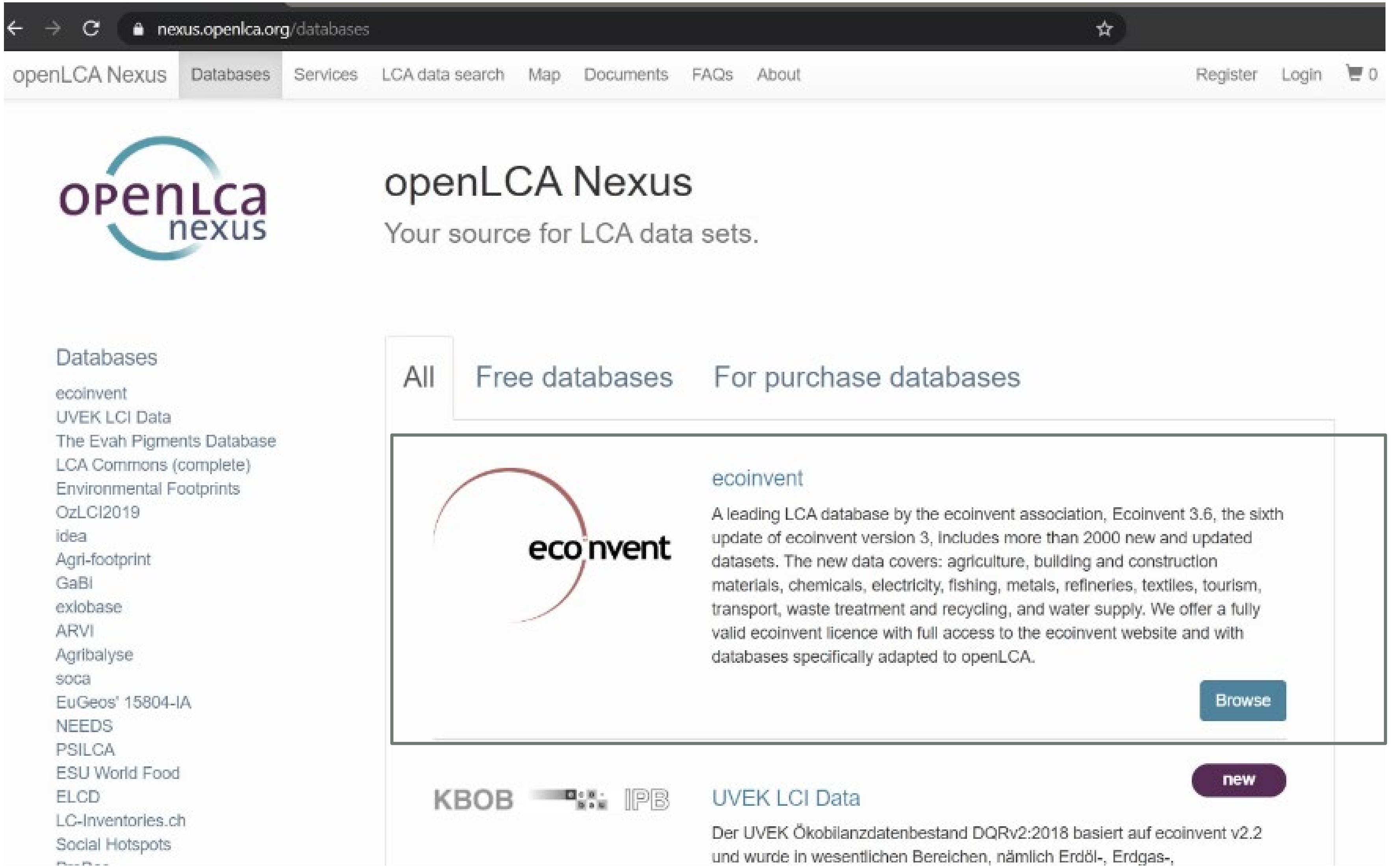
Functional unit

- **Functional equivalent (EN 17472):** quantified functional and/or technical requirements for a building or civil engineering works or an assembled system
  - civil engineering works type (road A to B); relevant technical/functional requirements (X vehicles); use pattern (expected vehicles per year); service life.
  - Example 1: "a dual carriage way" from A to B capacity for 20000 cars per day and the civil engineering works assessed is the dual carriageway plus additional communication cables, all the impacts of the asset as built are included
- **Functional equivalent (EN 15978):** denoting the technical characteristics and functionalities of the building that is being assessed.
  - Building type, technical and functional requirements, use, service life
  - Example: concrete building, one family dwelling, 50 years service life
- **Functional unit (EN 15804):** quantification of identified functions or performance characteristics of products.
  - Reference Unit, use and/or quality, service life
  - Example 1 (building level): m^2 net surface office, 50 years service life
- **Declared unit (EN 15804)** does not cover the whole building lifecycle ('cradle to grave') but only certain module ('cradle to gate').
  - Concrete ('cradle to gate') → Mass (kg)

Life cycle inventory (LCI): what processes?



Life-cycle inventory (LCI): databases



Life-cycle inventory (LCI): Environmental Product Declaration (EPD)

ENVIRONMENTAL PRODUCT DECLARATION
as per *ISO 14025* and *EN 15804+A1*

Owner of the Declaration	ArcelorMittal Europe
Programme holder	Institut Bauen und Umwelt e.V. (IBU)
Publisher	Institut Bauen und Umwelt e.V. (IBU)
Declaration number	EPD-ARC-20210132-CBB2-EN
Issue date	19.07.2021
Valid to	18.07.2026

Recycled and renewably produced
steel sections and merchant bars
Mittal Europe

.com | https://epd-online.com

Institut Bauen und Umwelt e.V.

ECO PLATFORM EPD EN 15804 VERIFIED

ArcelorMittal

LCA: Results

DESCRIPTION OF THE SYSTEM BOUNDARY (X = INCLUDED IN LCA; MND = MODULE NOT DECLARED; MNR = MODULE NOT RELEVANT)

PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END OF LIFE STAGE				BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARIES
Raw material supply	Transport	Manufacturing	Transport from the gate to the site	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling-potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	MND	MND	MND	MND	MNR	MNR	MNR	MND	MND	MND	MND	X	X	X

RESULTS OF THE LCA - ENVIRONMENTAL IMPACT according to EN 15804+A1: 1 metric to of XCarb™ structural steel sections

Parameter	Unit	A1-A3	C3	C4	D
Global warming potential	[kg CO_2-Eq.]	3.33E+2	1.60E+0	1.43E-1	2.14E+2
Depletion potential of the stratospheric ozone layer	[kg CFC11-Eq.]	4.84E-11	4.69E-14	7.83E-16	-4.74E-12
Acidification potential of land and water	[kg SO_2-Eq.]	7.46E-1	2.99E-3	8.57E-4	3.22E-1
Eutrophication potential	[kg $(PO_4)^{3-}$-Eq.]	7.51E-2	4.48E-4	9.72E-5	1.25E-2
Formation potential of tropospheric ozone photochemical oxidants	[kg ethene-Eq.]	8.27E-2	2.60E-4	6.58E-5	1.16E-1
Abiotic depletion potential for non-fossil resources	[kg Sb-Eq.]	4.04E-4	4.70E-7	1.44E-8	5.13E-4
Abiotic depletion potential for fossil resources	[MJ]	3.81E+3	1.82E+1	1.95E+0	1.94E+3

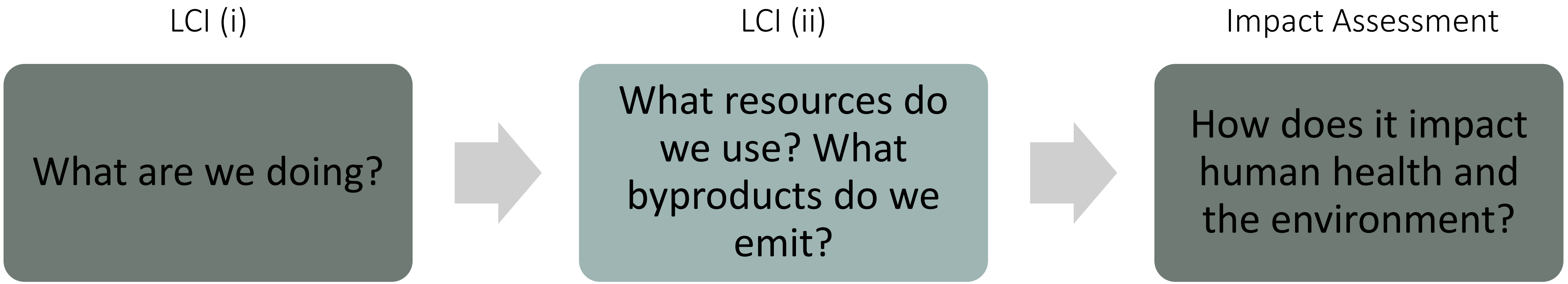
https://europe.arcelormittal.com/sustainability/xcarb/RRP/recycled-and-renewably-produced-flat-long-epd

Detailed impact assessment

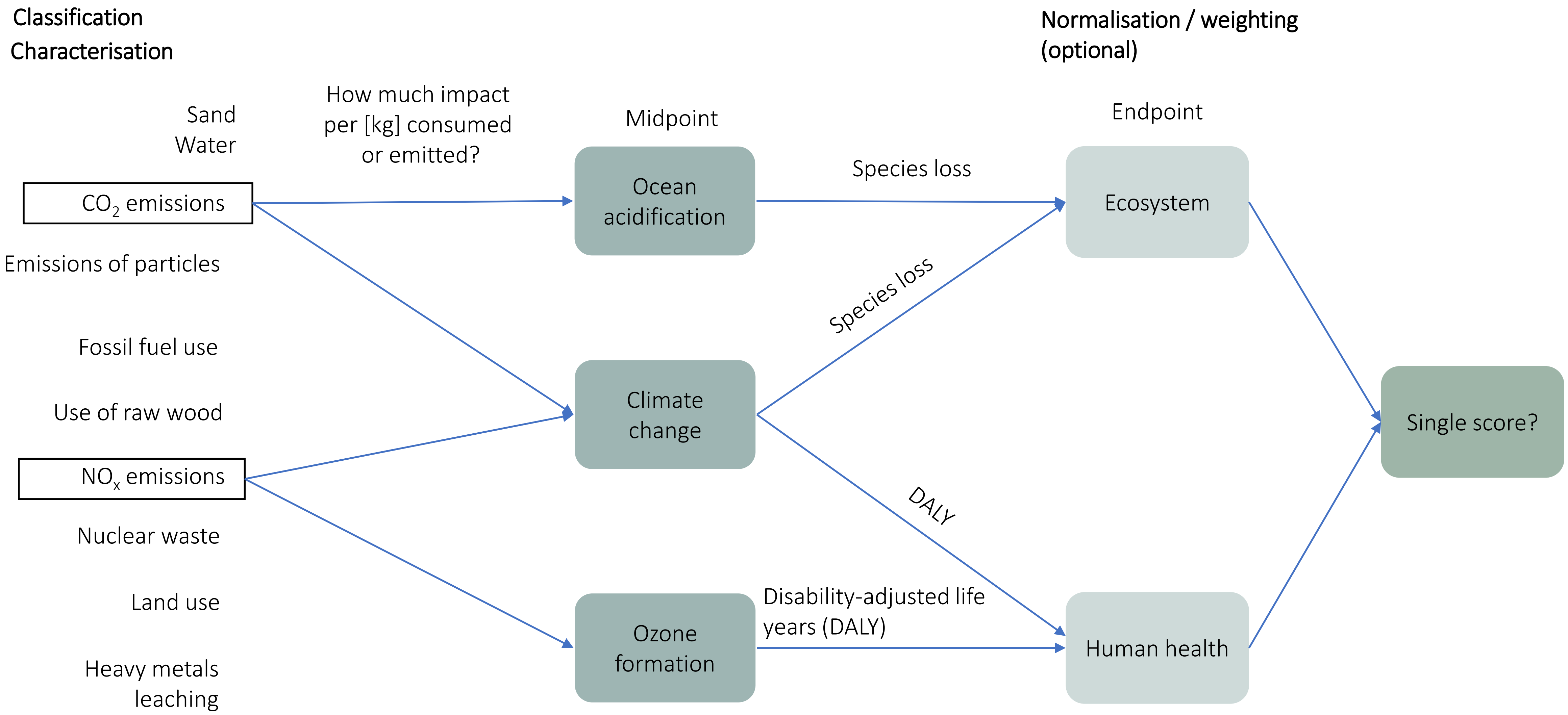
Results of the Inventory:

- Inputs (resources) from the environment
- Outputs (emissions) to the environment

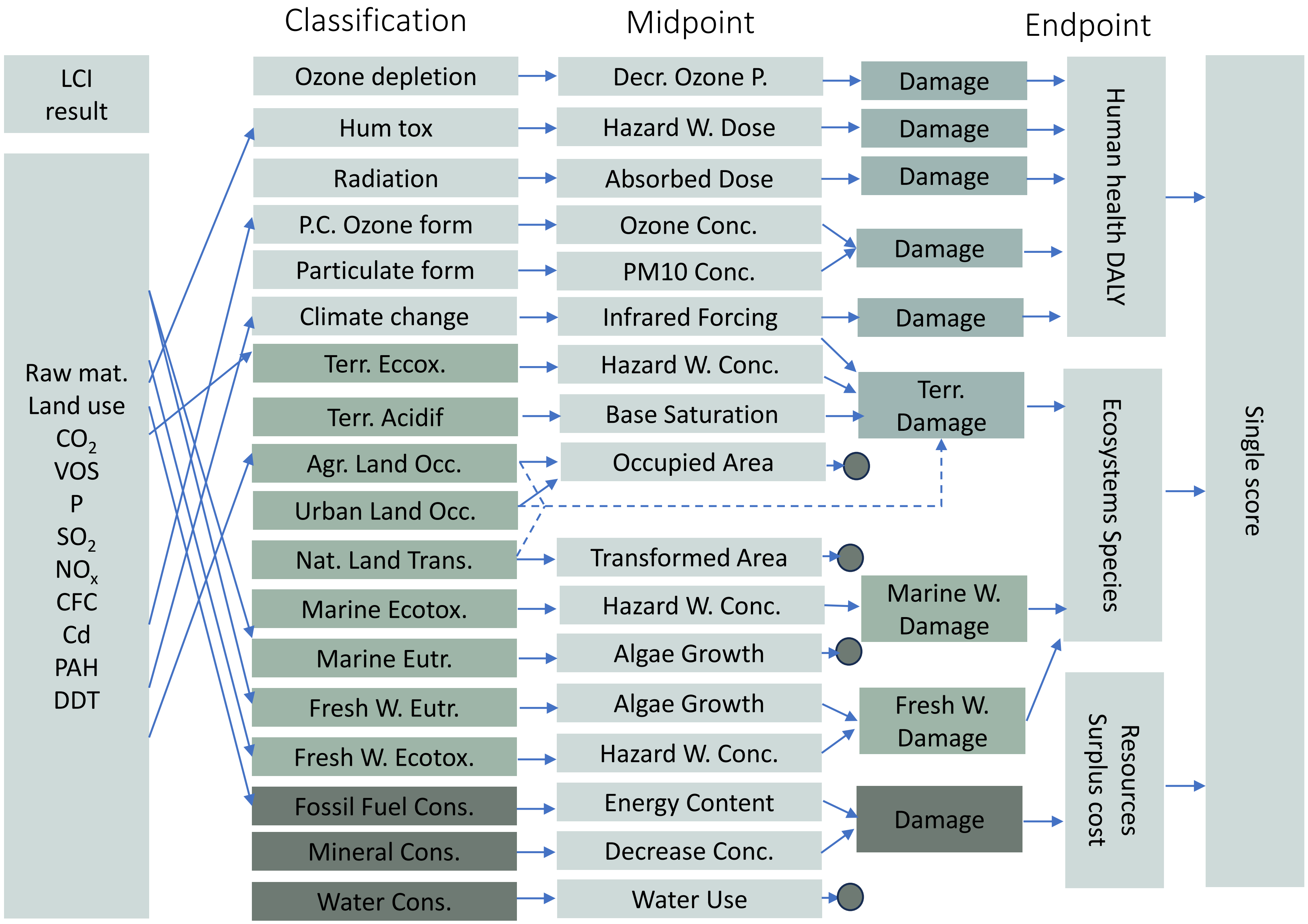
What effects do the inputs and outputs have on the environment?



Detailed impact assessment



Detailed impact assessment



Impact categories

https://ecochain.com/blog/impact-categories-lca/

Impact Category / Indicator	Unit	Description
Climate change – total, fossil, biogenic, and land use	kg CO_2-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 causes the destruction of 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 sulfur oxides
Fresh water eutrophication	kg PO_4-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 regionalized water scarcity factors.
Land use	Dimensionless	Measure of the changes in soil quality (Biotic production, Erosion resistance, Mechanical filtration).
Ionizing 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

Simplified impact assessment

- Impact assessments for infrastructure is very complex: practitioners often use simplified assessments.

- Common practice assess only…
  - Construction and operational energy use.
  - One impact category: Global Warming Potential

Definitions

- **Global warming potential (GWP)**: factor describing the radiative forcing impact of one mass-based unit of a given greenhouse gas relative to an equivalent unit of CO_2 over a given period of time
- **Greenhouse gases (GHGs)**: gaseous constituents of the atmosphere, natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds
- **Greenhouse gas (GHG) emission**: total mass of GHG released to the atmosphere over a specified period of time
- **Carbon dioxide equivalent (CO_2e)**: unit for comparing the radiative forcing of greenhouse gases (GHGs) to carbon dioxide

Simplified impact assessment: carbon dioxide equivalent

Embodied Carbon: sum impact of all the greenhouse gas emissions attributed to the materials throughout their life cycle

The carbon emissions emitted producing asset's materials, their transport and installation on site as well as their disposal at end of life.

Operational Carbon: the emissions of carbon dioxide during the operational or in-use phase.

a new asset with net zero operational carbon does not burn fossil fuels, is 100% powered by renewable energy, and achieves a level of energy performance in-use in line with the national climate change targets.

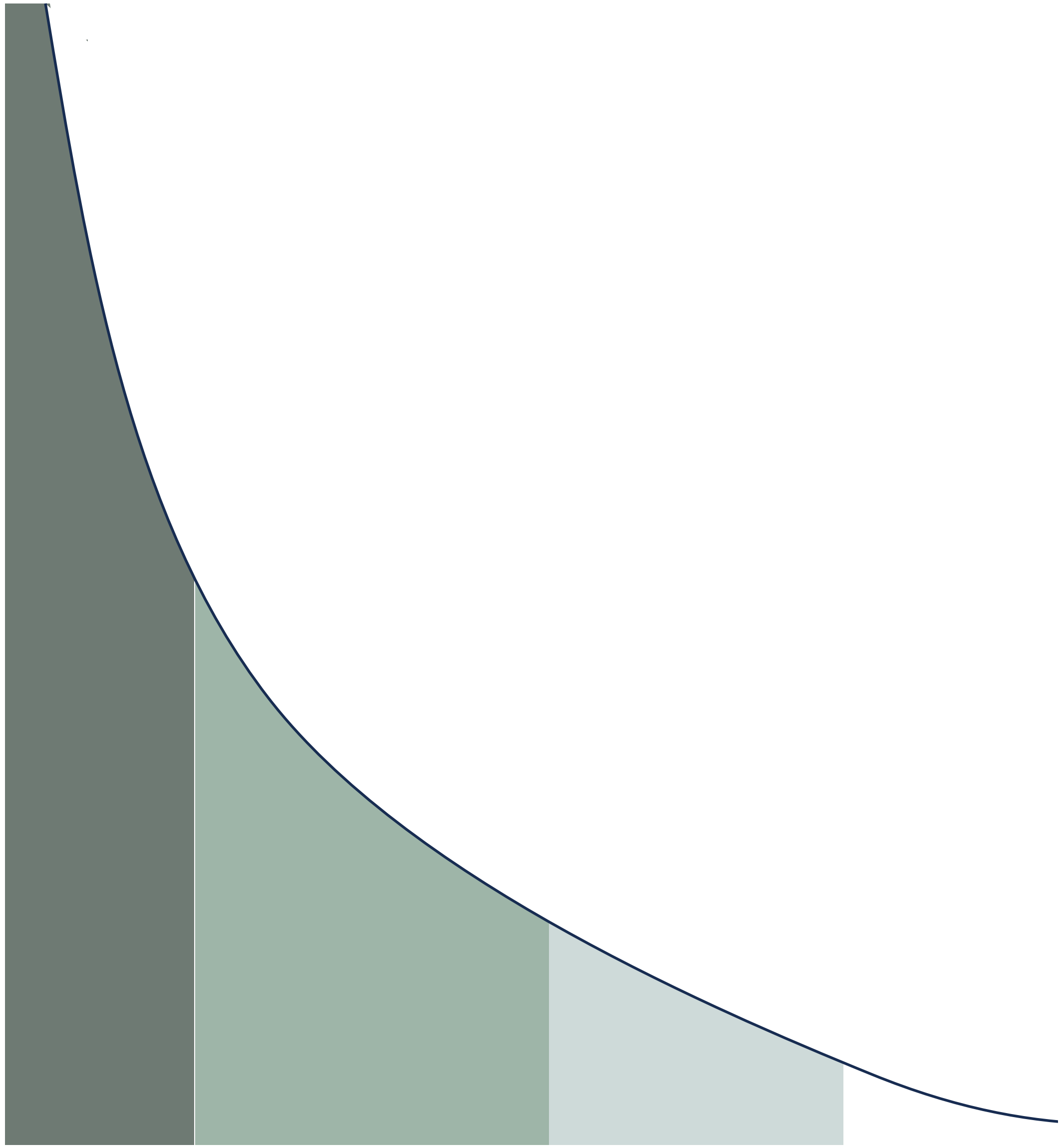
Simplified impact assessment: embodied carbon

1. Define goal and boundaries.
2. Estimate quantities of materials, products and processes in the asset.
3. Assess the carbon equivalent emissions for each material/product and process and then sum them to obtain the overall carbon
4. Interpret the results, refine and re-iterate if needed.

Inventory	×	Impacts	=	Total
Estimate the material quantities and processes in the building		Estimate the environmental impacts for each material and processes		Estimate the total environmental impact of the building
100 kg steel	×	0.43 $kgCO_2e$	=	43 $kgCO_2e$

Product stage		
A1	A2	A3
Raw material supply	Transport	Manufacturing

Carbon tools



[UKGOV Carbon Planning Tool]

[Institution of Structural Engineers – How to calculate embodied carbon]

[The Structural Carbon tool]

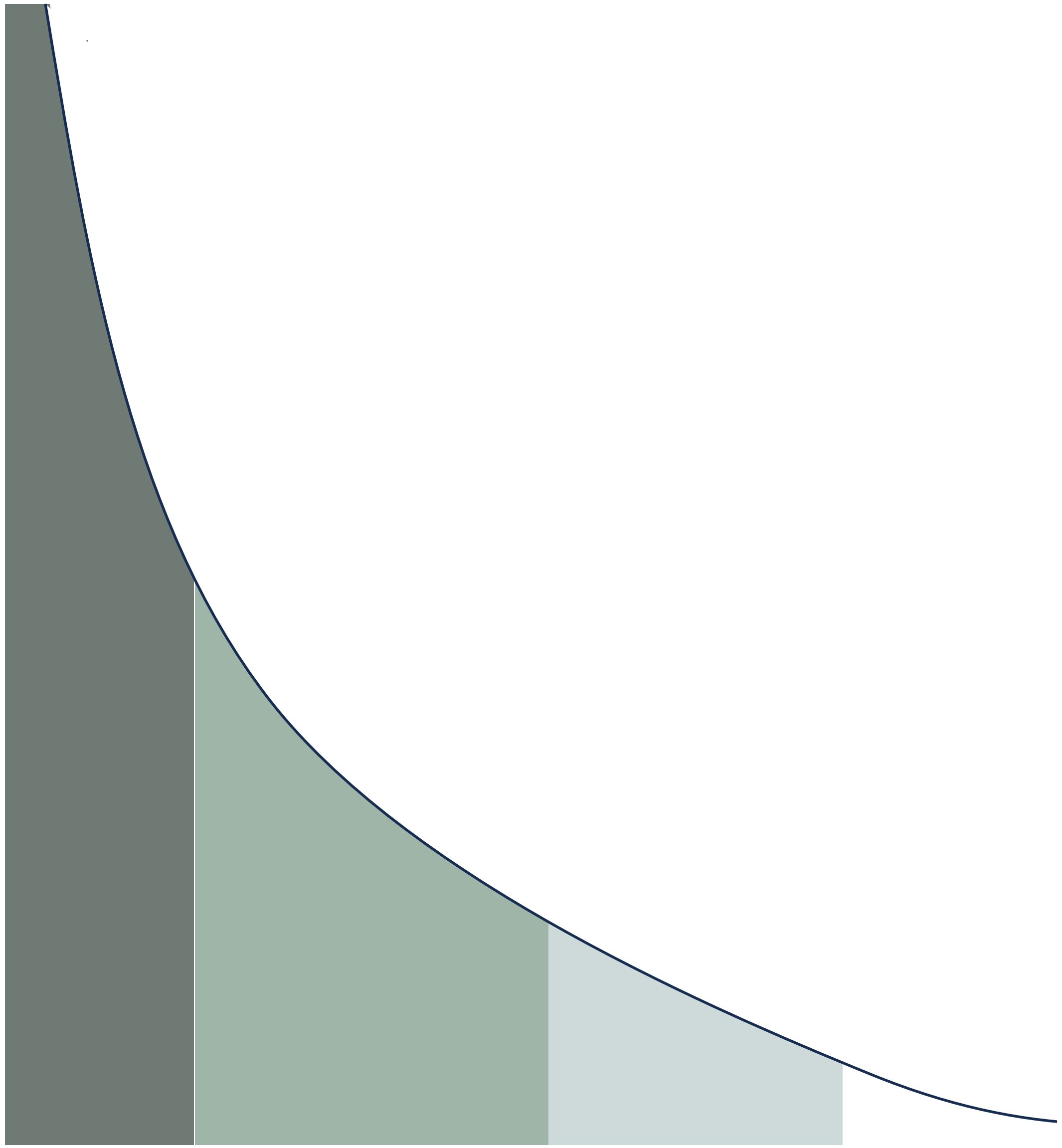
[National Highways Carbon emissions calculation tool]

[Rail RSSB Carbon Tool]

[Asphalt Pavement Embodied Carbon Tool]

[Steel Bridges Carbon Calculator by Atkins]

Useful links



LCA data | openLCA.org

Search | Database | ÖKOBAUDAT (oekobaudat.de)

EPD Library | EPD International (environdec.com)

ECO PORTAL - Eco Platform en (eco-platform.org)
Ramboll Microsoft Power BI

Bombyx | Food4Rhino

Cardinal LCA, a product by Pathways | Food4Rhino

EPiC Grasshopper | Food4Rhino

Free student license | One Click LCA
CAALA for Rhino | Food4Rhino

SUMMARY

- Definition and purpose of LCA in assessing the environmental impact of products and projects.
- Goal and scope definition, inventory analysis, impact assessment, and interpretation.
- Overview of available LCA software and tools for streamlining assessments.

ACTIVITY 3: Carbon emissions management

- Overview of embodied carbon emissions and their significance in infrastructure projects.
- Strategies to minimise embodied carbon emissions.
- Carbon management and whole life costing

Carbon management in infrastructure projects

Decarbonisation reviews accentuated the need for the following actions:

• focusing on **whole life carbon** both within the **control and influence** of asset owners/managers, not just in creating assets, but also in their future operation and use;

• considering assets as **part of complex, interconnected networks and systems**;

• accounting for and integrating **the carbon implications** of **climate resilience**, environmental **regeneration** and **biodiversity**; and

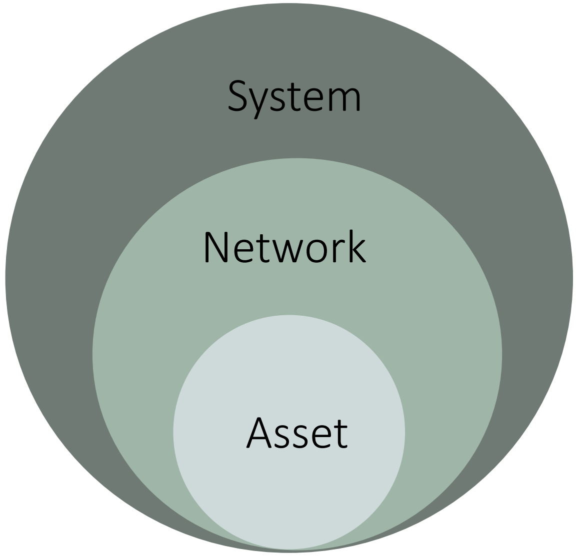
• recognising that most of the built environment expected to exist in 2050 is already built and has **locked in high carbon quantities**, hence the need for **retrofitting** to decarbonise established built environment systems.

From PAS2080 Carbon management in buildings and infrastructure

Lifecycle of infrastructure

<table>
<tr><td>Need</td><td colspan="4">Optioneering</td><td colspan="2">Design</td><td colspan="2">Delivery</td><td colspan="2">Operation</td><td>Purpose & performance review</td></tr>
<tr><td>Strategy</td><td>Prepa-ration & brief</td><td colspan="2">Concept</td><td>Defini-tion</td><td colspan="2">Technical design</td><td>Manufacture, construct & commission</td><td colspan="2">Hand-over & closure</td><td>Use</td><td>End of life</td></tr>
<tr><td>Strategy</td><td colspan="2">Preparation and briefing</td><td colspan="2">Concept design</td><td>Technical design</td><td>Spatial coordi-nation</td><td>Manufacture & construction</td><td colspan="2">Hand-over</td><td>Use</td><td>End of life</td></tr>
</table>

PAS2080:2023	Carbon management in buildings and infrastructure
BS 8536:2022	Design, manufacture and construction for operability
RIBA Plan of Work	Model for the design and construction process of buildings



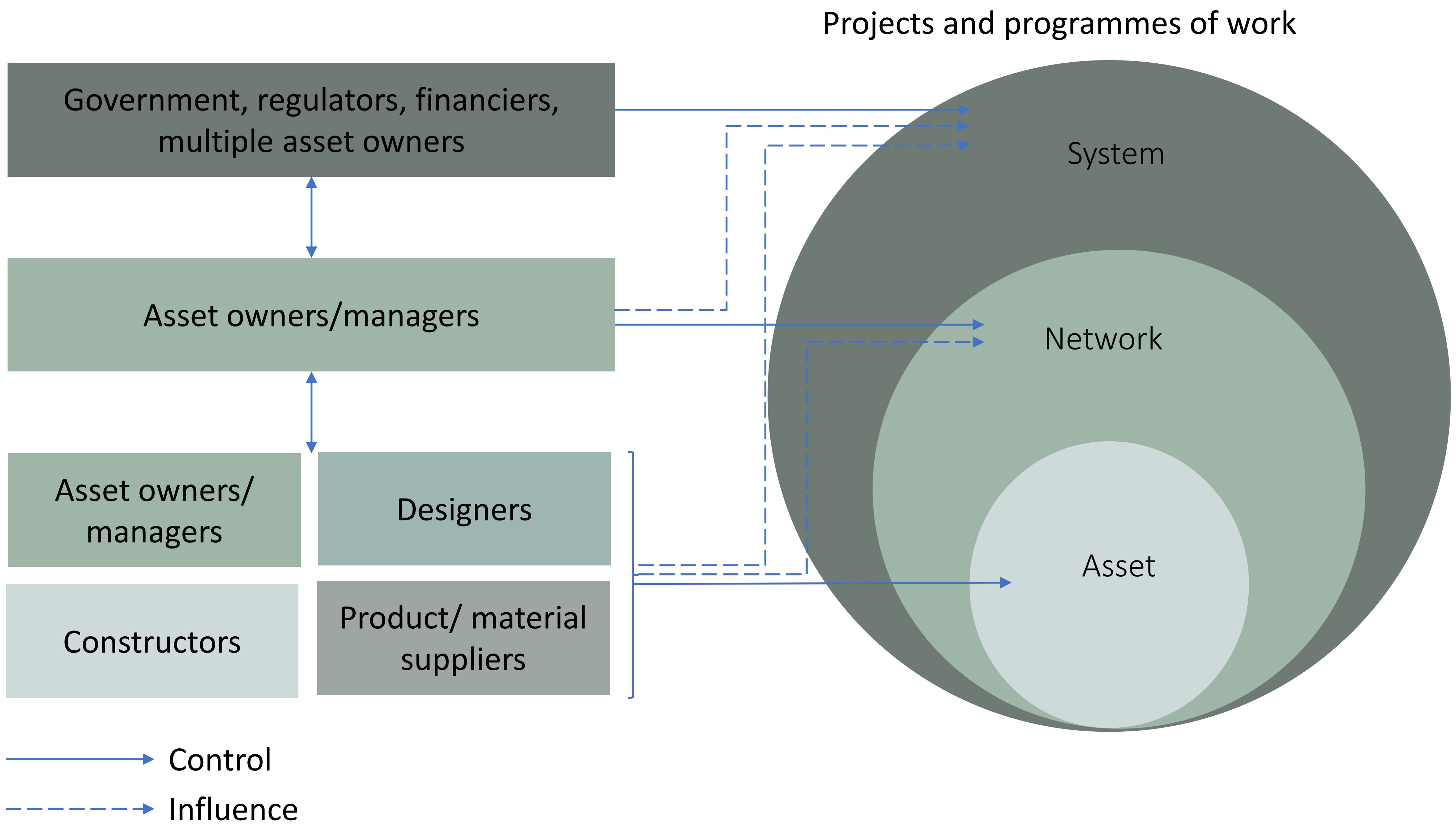
Capital carbon

Capital Carbon: 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

- "capital carbon” is the selected terminology to allow comparison/alignment with the cost management/expenditure profile of projects and/or programmes of work
- "user carbon" greenhouse gas emissions associated with users’ utilization of an asset, network and/or system, and the service it provides during operation
- emissions associated with maintenance and refurbishment are included as “optional” under the capital carbon definition because they could also be defined as “operational carbon” emissions, depending on the chosen assessment methodology
- “embodied carbon” and “upfront carbon” terminologies are acknowledged by parts in accordance with existing life cycle assessments standards and guidance

From PAS2080 Carbon management in buildings and infrastructure

Decarbonisation principles

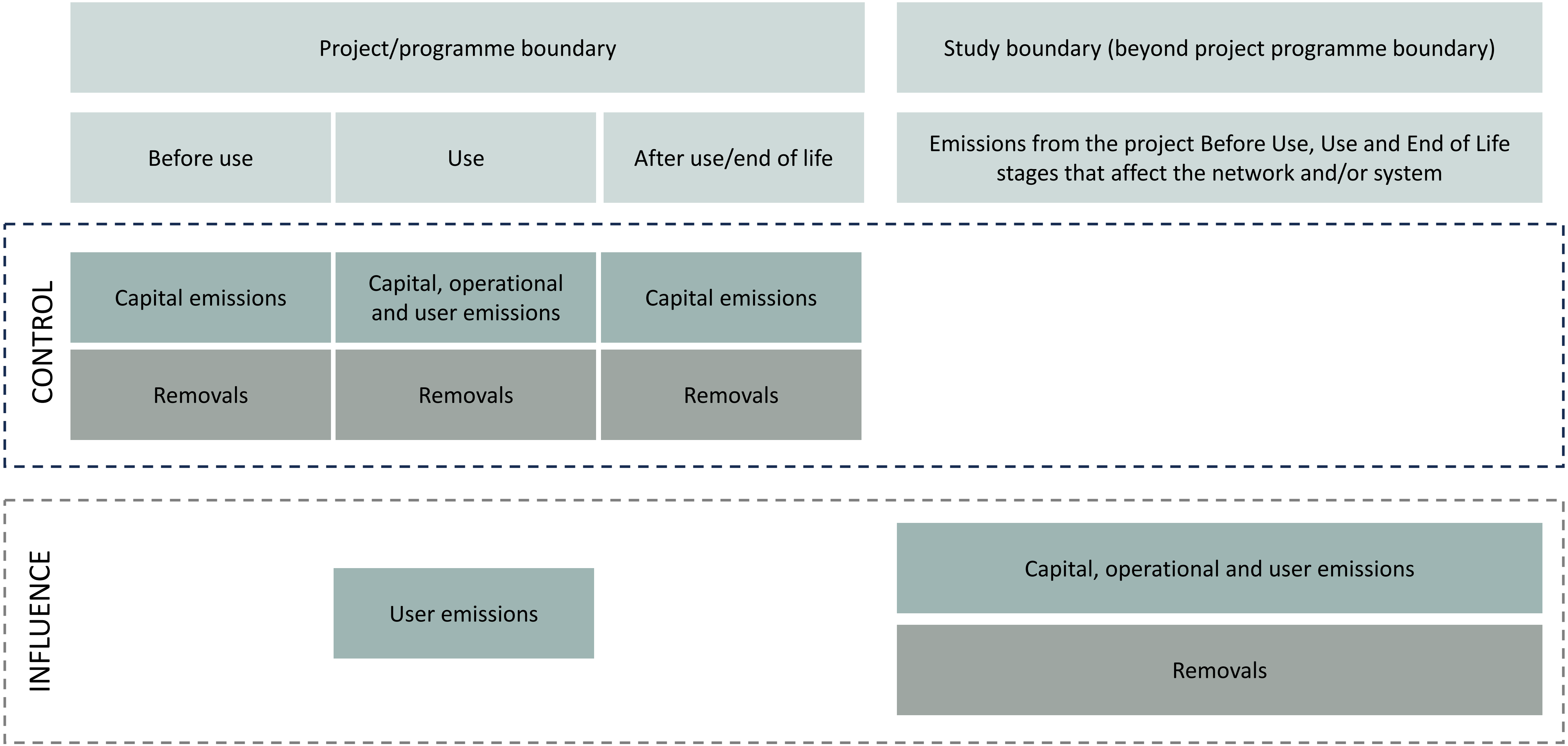


Decarbonisation principles

- Decarbonisation should be approached from the **system level down**, requiring collaboration across the value chain; by setting carbon management requirements and recognising the key role of governments and regulators.
- Achieving net zero **requires asset owners and managers** to understand the **complex interdependencies** between decarbonisation, climate adaptation, biodiversity loss, and socio-economic priorities.
- The carbon management process integrates **sustainability criteria** into **decision-making** in the built environment, promoting holistic approaches to address environmental and social challenges.

From PAS2080 Carbon management in buildings and infrastructure

Decarbonisation principles



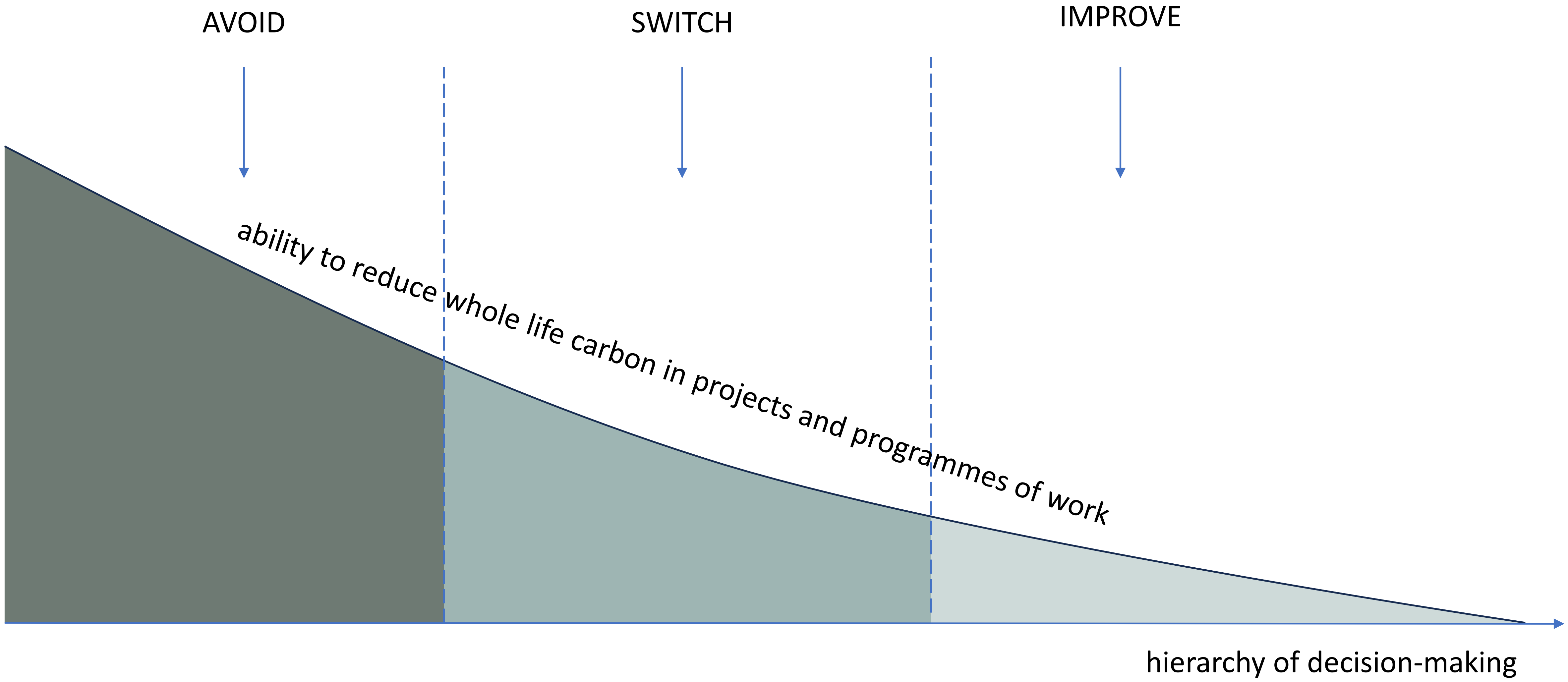
Adapted from PAS2080 Carbon management in buildings and infrastructure

Decarbonisation principles

- **Identify all activities** that result in carbon emissions or removals they control and influence, at the *asset, network and system level.*
- Identify **interdependencies**, synergies and relationships between their own project and/or programme of works and the network and system, and engage with relevant stakeholders to identify carbon reduction opportunities and risks at an *asset, network and system level*.
- Prioritise **nature-based solutions** for reduced whole life carbon emissions and potential for carbon removal, as well as the associated co-benefits.
- **Engage** with other **value chain members** or other stakeholders (such as planning authorities, financiers, government and regulators, among others) to align approaches to carbon reduction and maximize decarbonisation opportunities.
- Identify the **work stages** within which they have control or influence in terms of identifying, managing or delivering **low-carbon solutions**.
- **Assess** emissions and removals in accordance with the whole life carbon framework.
- Demonstrate that the level of **accuracy** appropriate for informing decision-making at the stage of the project or programme has been taken into account.
- **Integrate** whole life carbon reduction in their **decision-making** processes.

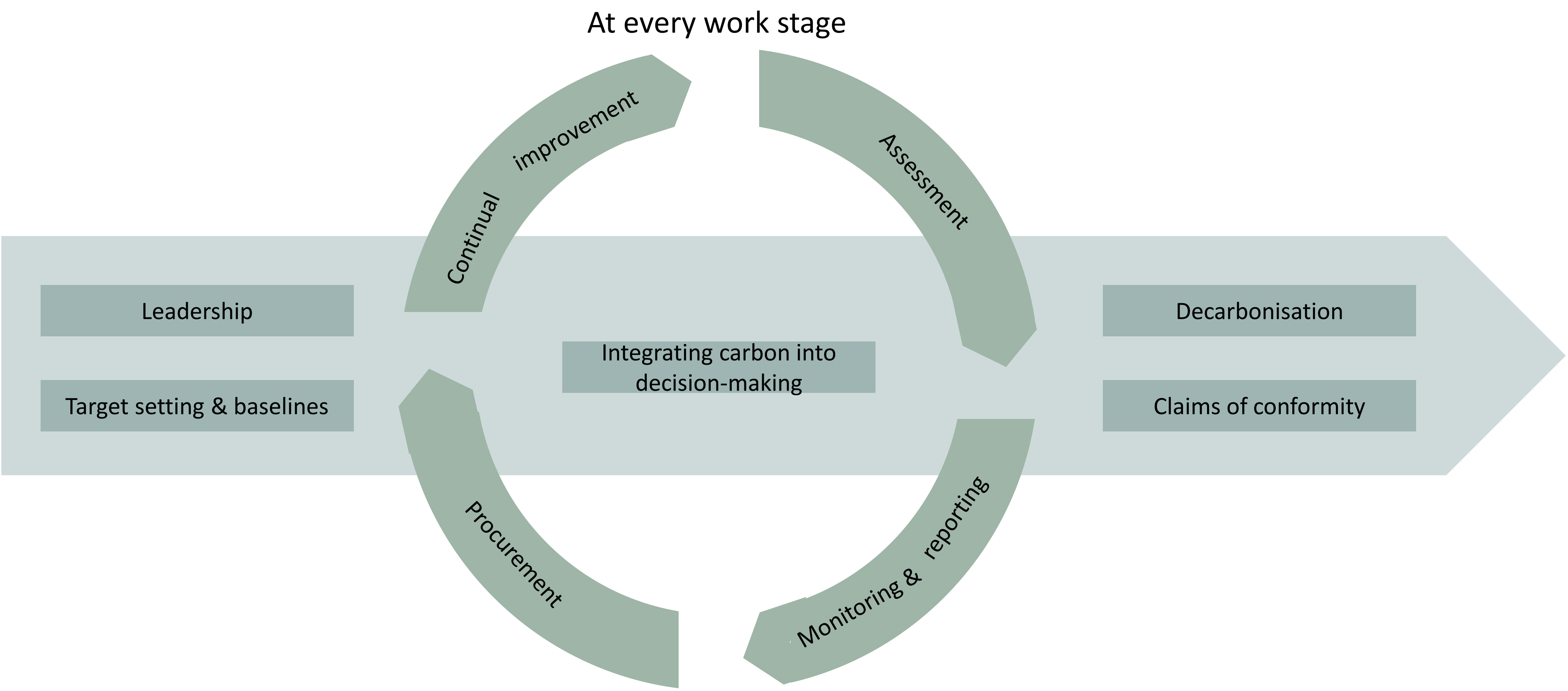
From PAS2080 Carbon management in buildings and infrastructure

Carbon reduction hierarchy



Adapted from PAS2080 Carbon management in buildings and infrastructure

Integration of carbon management in decision making



Adapted from PAS2080 Carbon management in buildings and infrastructure

Implementation of carbon management processes

- **Understand and prioritise** the requirements of the carbon management process for delivering the project and/or programme of work as established by the asset owner/manager.
- **Identify** whole life **carbon reduction opportunities** over which they have control and/or influence, according to the carbon reduction hierarchy presented before, and take early action to reduce carbon emissions where the opportunity is greatest.
- **Prioritise the implementation** of solutions that best support system-wide decarbonisation.
- **Challenge current practices** to enable whole life carbon reduction, including scope, strategy and intended outcomes, standards and prescriptive specifications, design approach, programme or cost.
- **Collaborate** with other stakeholders and value chain members to implement solutions that minimise whole life carbon.
- **Assess** whole life carbon emissions and removals in their control and influence and record reductions with reference to the baseline(s) and target(s) set.
- **Identify low-carbon alternatives** appropriate at each stage of the carbon reduction hierarchy, including nature-based solutions and circular economy opportunities in the project or programme, where appropriate.
- Where **carbon removal** activities are planned or undertaken, **report** them **separately** from carbon emissions and emissions reductions.

From PAS2080 Carbon management in buildings and infrastructure

Carbon assessments over the whole life of an asset, network, system

- **Assess whole life** emissions using appropriate assessment methodologies from existing lifecycle analysis standards and/or other recognized sources.
- **Identify the limitations** in existing methods and address these to meet the assessment requirements focusing on assessing whole life carbon to inform decision-making at the asset, network or system level.
- **Compare** the whole life carbon impact of **options** using the same assessment methodology for consistency.
- **Lifecycle standards** for buildings and other civil works (e.g. EN 17472, EN 15978, EN 15804) can be used to assess emission sources.

From PAS2080 Carbon management in buildings and infrastructure

Capital carbon impact assessment

1. Define goal and boundaries.
2. Estimate quantities of materials, products and processes in the building.
3. Assess the carbon equivalent emissions for each material/product and process and then sum them to obtain the overall carbon
4. Interpret the results, refine and re-iterate if needed.

Inventory	×	Impacts	=	Total
Estimate the material quantities and processes in the building		Estimate the environmental impacts for each material and processes		Estimate the total environmental impact of the building
100 kg steel	×	0.43 $kgCO_2e$	=	43 $kgCO_2e$

Product stage		
A1	A2	A3
Raw material supply	Transport	Manufacturing

Whole-life carbon assessment principles to support decision-making

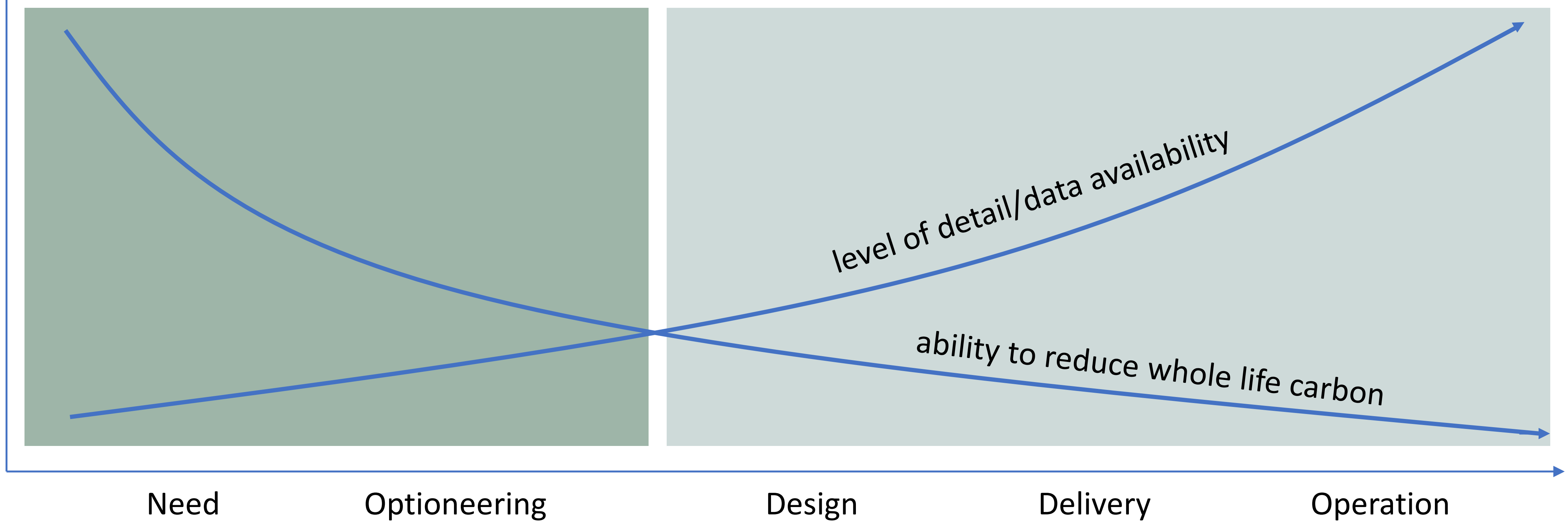
Assess the whole life carbon within a comprehensive **study boundary (within and beyond the project/programme boundary)** – impacts of an asset or its network system.

Availability of data likely to be limited. Work with **benchmarks** and/or available **carbon factors**, **prioritise** assessment of activities that support identification of lowest carbon solution.

Assess emissions within a comprehensive study boundary that covers **all relevant sources** of all whole life carbon emissions and removals for the project programme.

Identify impact on **network** and **system.**

Availability of data and detail of assessment to improve.



Adapted from PAS2080 Carbon management in buildings and infrastructure

Target setting/baselines, monitoring and reporting

- Carbon reduction targets must be based on **clear baselines** to assess performance effectively.
- **Targets** should be set at the **system level** and aligned with **network** and **asset-level** goals.
- **Asset-level targets** are essential for achieving system-level net zero objectives.
- Carbon management requires **robust monitoring** and frequent transparent reporting to track progress against targets.
- **Reports** should guide decision-making on whole life carbon management and inform **future improvements**.

From PAS2080 Carbon management in buildings and infrastructure

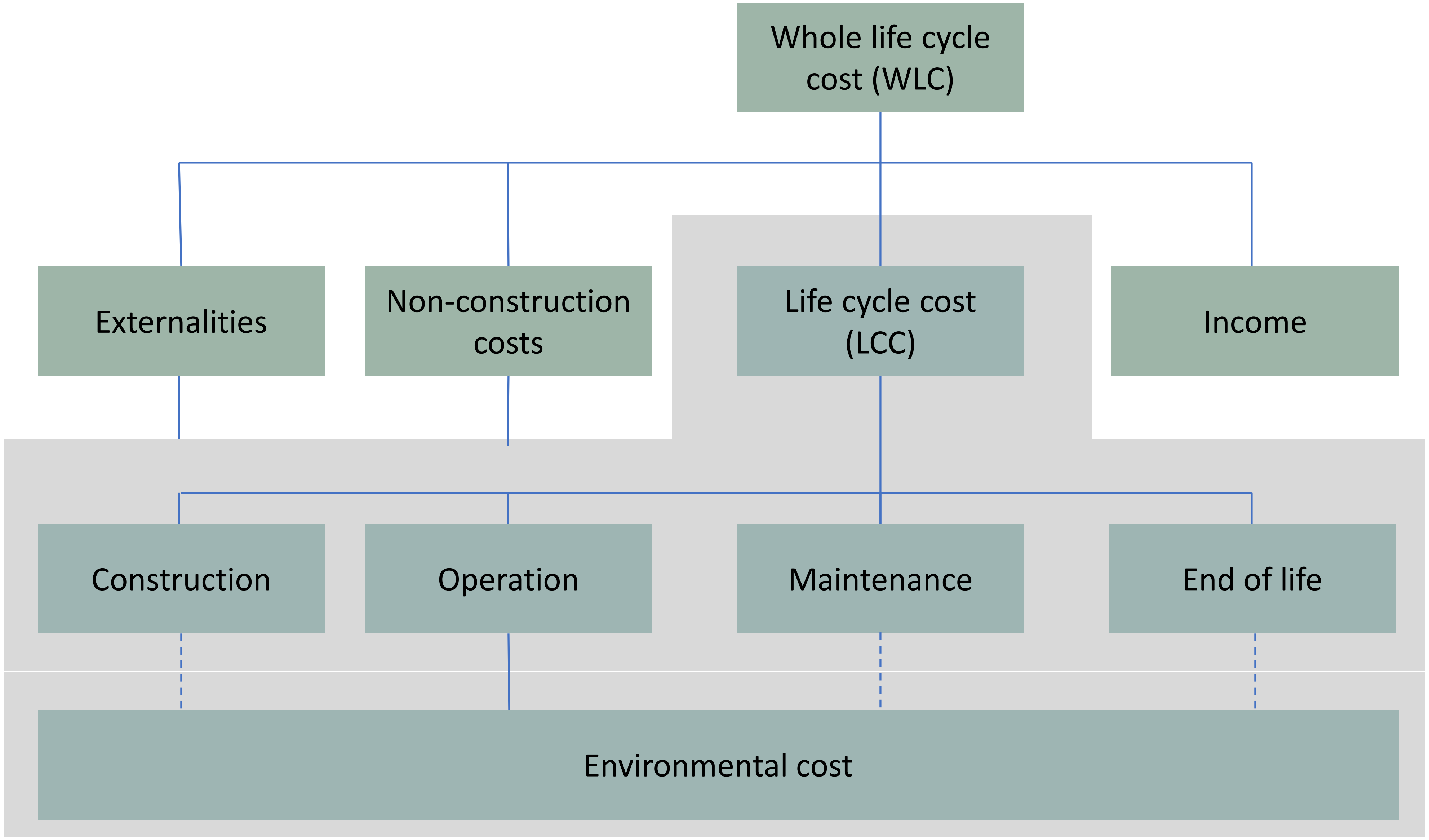
Life cycle costing

- When considering costs (analogous to the LCA), the following question arise:
  - How do the costs/price of a product develop over its life cycle?
  - How sensitive are costs and prices to individual factors (e.g. fluctuations in the oil price)?

- Similar to cost unit accounting in business administration (costs of a product are tracked along its path in the company or its cost trend is determined)
- There are also other types of cost accounting in business administration, such as cost center accounting (costs for a process or process area in a company independent of the product)

Prices behave independently of costs, they are also dependent on market events.
Thus, price ≠ cost !

Life cycle costing



ISO 15686-5: Buildings and constructed assets – Service life planning – Part 5: Life-cycle costing

Whole life cost

- **Whole life cost (WLC)**
  - **Non-construction costs**
    - Land and enabling works → Site costs (land and any existing building)
    - Finance → Interest or cost of money and wider economic impacts
    - User support costs: property management → In-house resources and property management
    - User support costs: user charges → Unitary, parking, facilities charges
    - User support costs: administration → Reception, helpdesk, switchboard, IT, library, …
    - Taxes → Taxes on non-construction items
    - Other
  - **Income**
    - Income from sales → Residual value on disposal of interest in land, constructed assets…
    - Third party income during operation → Rent and service charges
    - Taxes on income → On land transactions
    - Disruption → Downtime, loss of income
    - Other
  - **Externalities**
  - **Life cycle cost (LCC)**

Life cycle costing

Dynamic investment calculation to ISO 15686-5

- Net present value (NPV): Sum of discounted future cash flows (costs & incomes)
- Net Present Cost (NPC): Sum of discounted future costs
  - Reflects the time value of money
  - Cash flows from different points in time are made measurable at one point in time
  - Also takes into account the effects of inflation/deflation
  - Price increase effects can be also be accounted

EN 16627 Includes the principles of ISO 15686-5 but distinguishes between

- Life cycle costs in the narrower sense (Life Cycle Costs): includes only costs (expenditure)
- Life cycle costs in the broader sense (Whole Life Costs): includes both expenditure and income for assessing life cycle success/economic efficiency

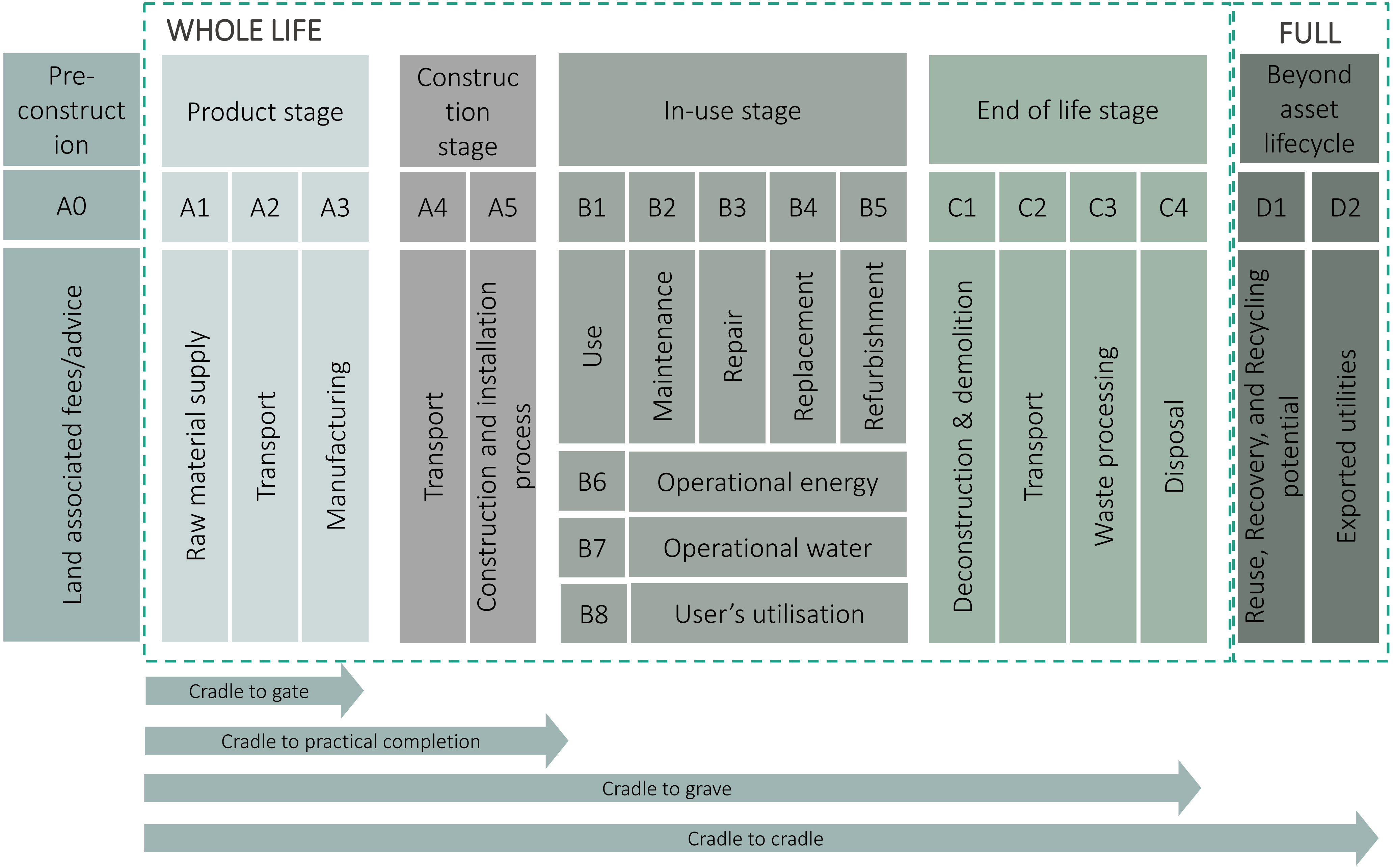
SUMMARY

- Overview of embodied carbon emissions and their significance in infrastructure projects.
- Strategies to minimise embodied carbon emissions.
- Carbon management and whole life costing

ACTIVITY 4: Case study on critical infrastructure

- Selection of databases, life-cycle inventories and assessment steps
- Evaluation of upfront carbon for conventional and sustainable solutions
- Selected industry case studies for infrastructure carbon management

Civil engineering works assessment system boundary



From EN17472 Sustainability of construction works. Sustainability assessment of civil engineering works. Calculation methods.

Simplified impact assessment A1-A3

1. Define goal and boundaries.
2. Estimate quantities of materials, products and processes in the building.
3. Assess the carbon equivalent emissions for each material/product and process and then sum them to obtain the overall carbon
4. Interpret the results, refine and re-iterate if needed.

Product stage		
A1	A2	A3
Raw material supply	Transport	Manufacturing

$\sum_{n\ materials}$ (Inventory × Impacts) = Total

Inventory	Impacts	Total
Estimate the material quantities and processes in the asset	Estimate the environmental impacts for each material and processes	Estimate the total environmental impact of the building

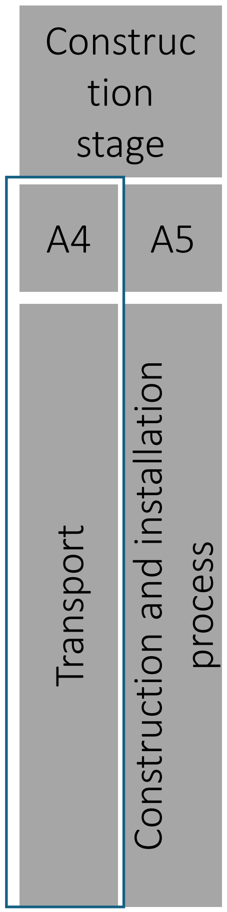
$\sum_{n\ materials}$ (100 kg steel × 0.43 $kgCO_2e$ ...) = 43 $kgCO_2e$ ...

Simplified impact assessment A4

Module A4 is concerned with transport of materials or products from the factory gate to the construction site, and the transport of construction equipment (cranes, scaffolding, etc.) to and from the site.

- Module A4 emissions may be significant for heavy civil works, but minor for buildings
- Some journeys comprise multiple legs over different transport modes.
- Reuse of components, materials or products that are locally sourced and transported over short distances will help to reduce both Module A4 and overall project emissions.

$$\sum_{n\ \text{materials}} \left(\text{Transport distance for } i \text{ material} \times \text{Emission factor per mode} \right) = \text{Total transport emissions}$$



Mode	Emission factor ($gCO_2e/kg/km$)
Road transport emissions, average laden	0.10749
Road transport emissions, fully laden	0.07375
Sea transport emissions	0.01614
Freight flight emissions	0.53867
Rail transport emissions	0.02782

from Gibbons et al., (2022)

Simplified impact assessment A5w

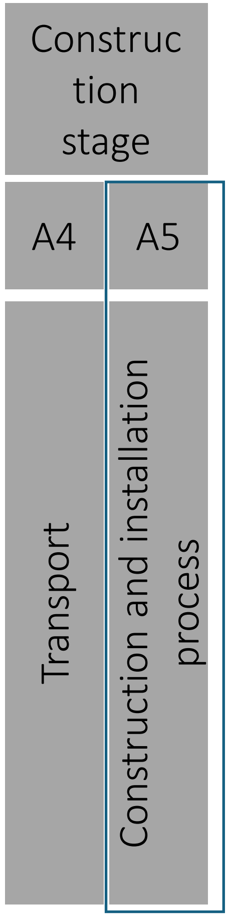
- Module A5 includes waste A5w, and energy use from machinery and temporary site office A5a

$$\sum \left[\text{Waste factor for } i \text{ material} \times \left(\text{Emissions factor for A1-A3} + \text{Emission factor for transport A4} + \text{Emission factor for transport C2} + \text{Waste processing C3-C4} \right) \right] = \text{Total waste emissions}$$

- Waste factor for *i* material → $WF_i = [1/(1 - WR_i) - 1]$

  WR_i = waste rate (quantity of materials brought to site that ends up as waste during installation/ construction) of i material using WRAP Net Waste Tool

- Emissions factor for A1-A3 → Embodied carbon factor for A1-A3 for i material
- Emission factor for transport A4 → Embodied carbon factor for transport to site A4
- Emission factor for transport C2 → Transportation away from site
- Waste processing C3-C4 → Waste processing and disposal embodied carbon factor



Material/product	WR (waste rate)	WRAP Net Waste Tool Ref	WF (waste factor)
Concrete in situ	5%	Table 2, Concrete in situ	0.053
Mortar	5%	Table 2, Gypsum	0.053
Screed	5%	Table 2, Screed	0.053

from Gibbons et al., (2022)

Simplified impact assessment A5a

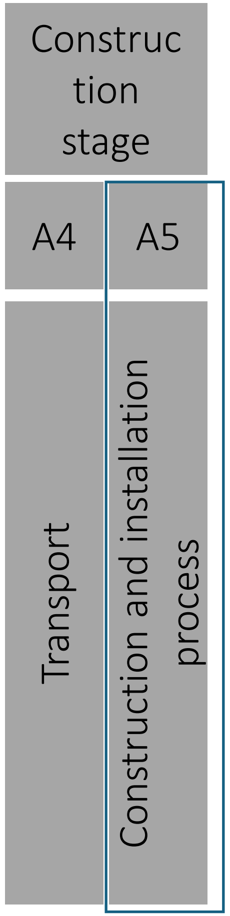
- Site activity emissions can be estimated from on-site electricity consumption and fuel use, and should be monitored during construction to contribute to an accurate as-built embodied carbon calculation at practical completion
- Any site activity emissions data collected can also be used to inform estimates of A5a emissions in future projects.
- Consider excavation, temporary works, etc.

Emission factor × Project cost / 100,000 = Emissions from site activities

Construction activities emission factor of 700kgCO_2e/£100,000 for superstructure and superstructure of a building; 1400kgCO_2e/£100,000 for the whole building

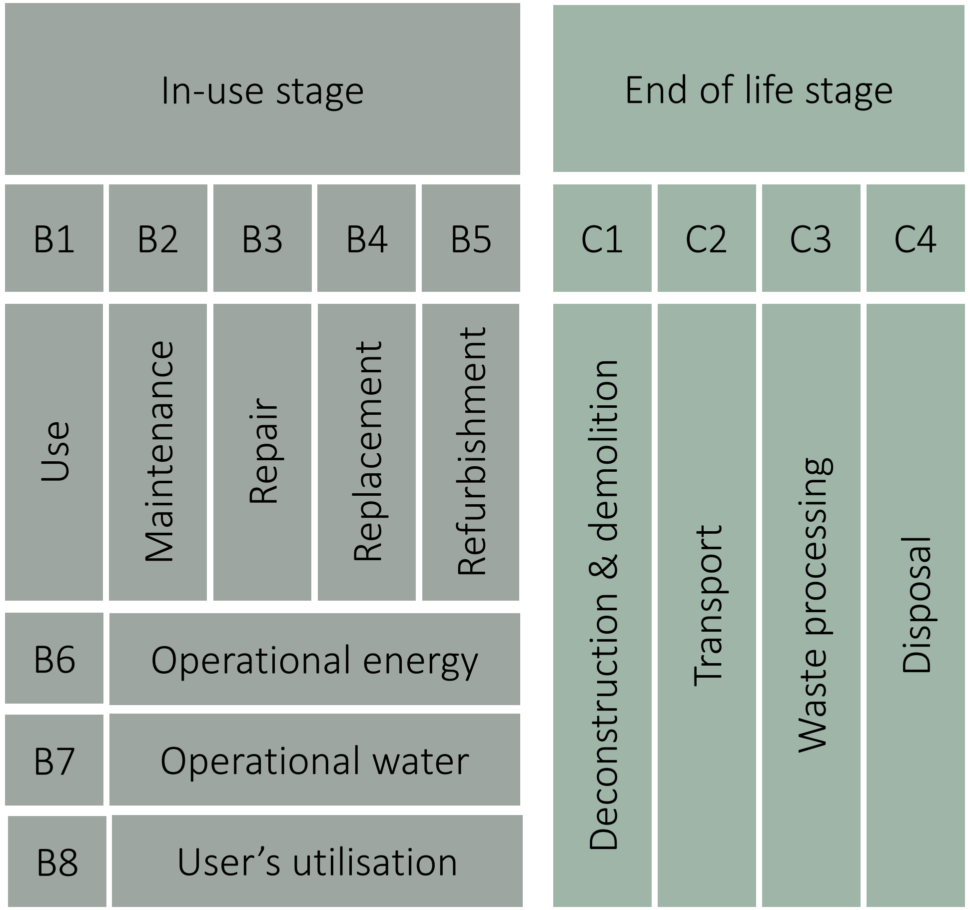
or

$\sum_{n\ activities}$ (Emission factor × Activity) = Total transport emissions



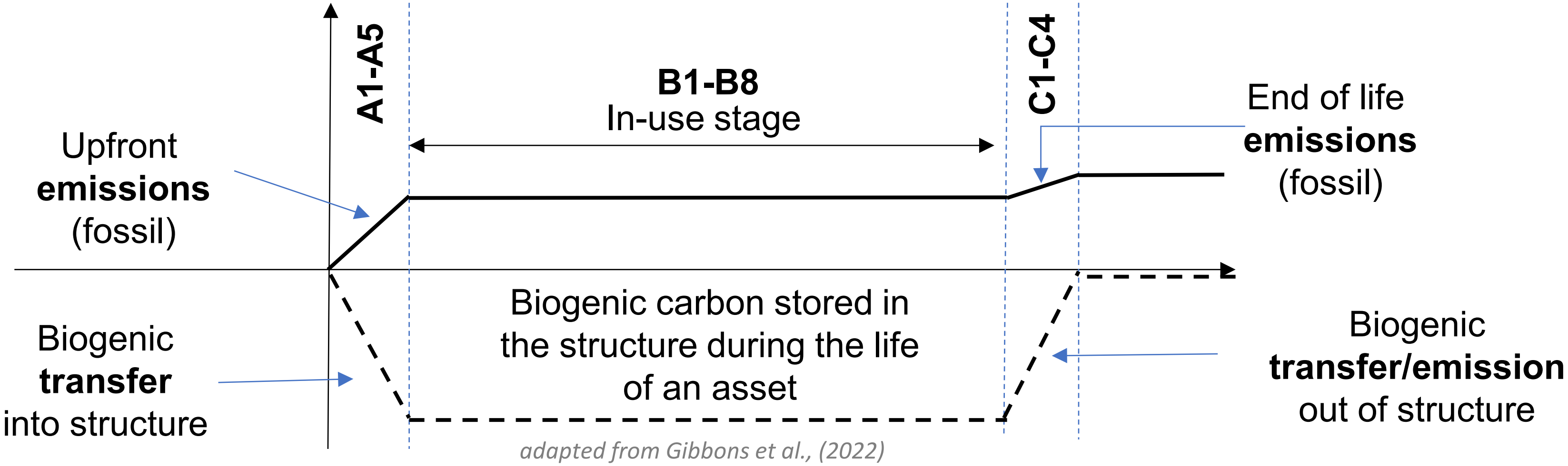
Simplified impact assessment B, C

- Similar approaches as for Module A
- Case-by-case scenario
- The carbon factor for Module B4 is the number of times a component is replaced in the built asset's life cycle multiplied by the sum of the carbon factors for life cycle modules A1–4, A5w and C2–C4
- Modules C1–C4 are likely to account for a small percentage of structural embodied carbon over the life cycle, unless timber products are used.



Carbon sequestration

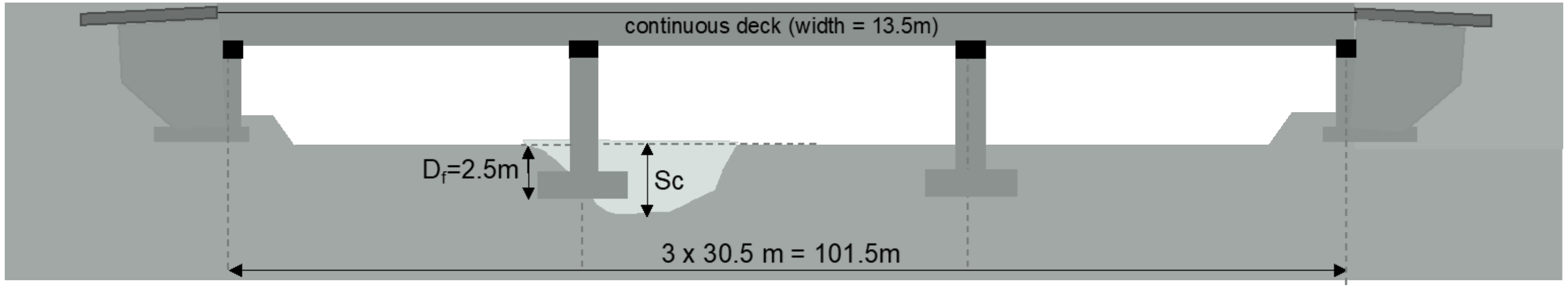
Biogenic carbon vs fossil carbon, and emissions vs transfers



adapted from Gibbons et al., (2022)

- Carbon dioxide is removed from the atmosphere as trees grow — via photosynthesis, known as 'sequestration'.
- The carbon element of this CO_2 is temporarily stored within timber until it is released at end of life in the form of a greenhouse gas (CO_2 or CH_4), for example by burning or decomposition of the timber; this stored carbon is known as 'biogenic carbon'.
- While fossil carbon is typically emitted due to the production/construction of a timber structure, biogenic carbon is instead transferred into the structure during production/construction.
- At the structure's end of life, the biogenic carbon is then either transferred out of the structure (e.g. sending the timber for reuse), emitted into the atmosphere (e.g. incineration for energy), or both (e.g. sent to landfill).
- Locking biogenic carbon into a timber structure is of climatic benefit for as long as the carbon is kept within that structure, though the storage itself does not negate the immediate effects of fossil carbon emissions (e.g. those emitted during the production of a timber beam).
- In the absence of product specific data, biogenic carbon sequestered can be assumed as $-1.64\text{kgCO}_2\text{e}$ per kg of timber

Assessment case study



adapted from Mitoulis et al., 2023

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

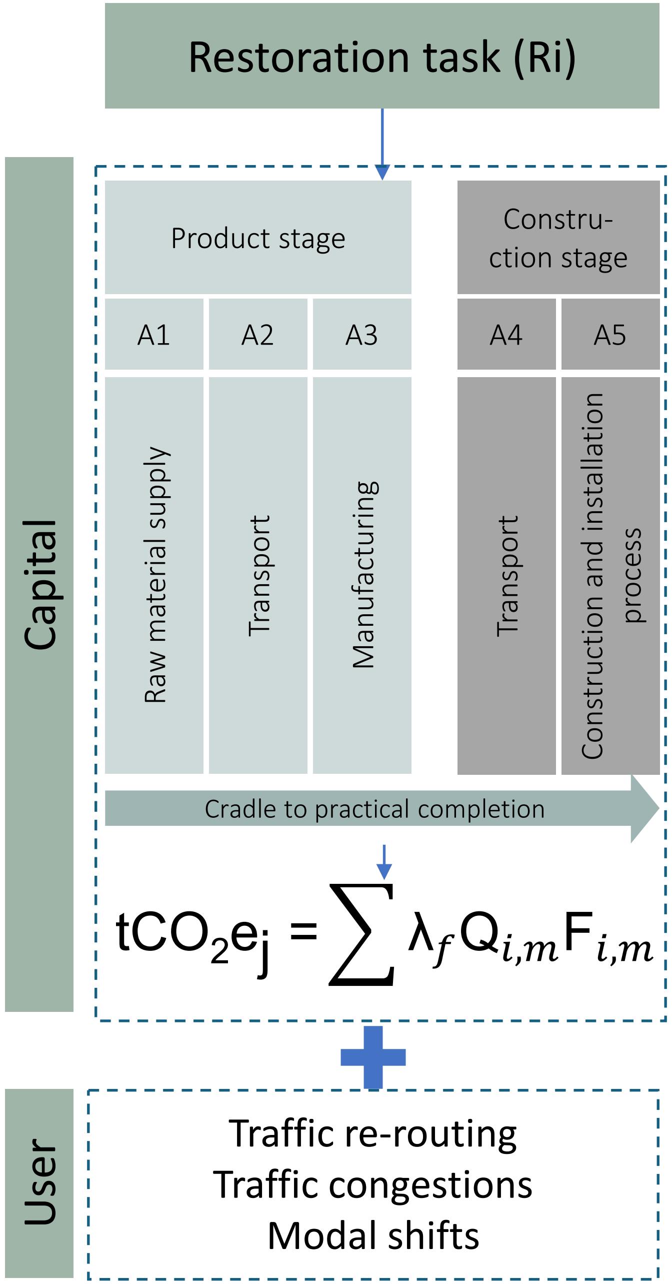
- **benchmark transport asset**, typical river-crossing 3-span bridge with shallow foundations under nine flood scenarios
- **vulnerability** for the as built and the deteriorated asset is estimated using **fragility** functions
- asset recovery is evaluated based on **restoration** (structural capacity) and **reinstatement** (traffic capacity) models
- restoration tasks were associated with various construction works and bill of quantities including the materials, on-site activities and transportation are based on the established methods

Restoration tasks considered

- R1 Armouring countermeasures and flow-altering/cofferdam (0.70/0.80/0.90/1.00)
- R2 Temporary support per pier (0.70/0.80/0.90/1.00)
- R5 Repair cracks and spalling with epoxy and/or concrete (0.50/0.70/0.85/1.00)
- R6 Re-alignment and/or levelling of pier (0.50/0.70/0.85/1.00)
- R11 Erosion protection measures (0.70/0.80/0.90/1.00)
- R12 Rip rap and/or gabions for filling of scour hole and scour protection (0.70/0.80/0.90/1.00)
- R14 Ground improvement per foundation (0.70/0.80/0.90/1.00)
- R15 Installation of deep foundation system (1.00/1.00/1.00/1.00)
- R16 Extension of foundation footing (1.00/1.00/1.00/1.00) f
- 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.

Embodied carbon assessments

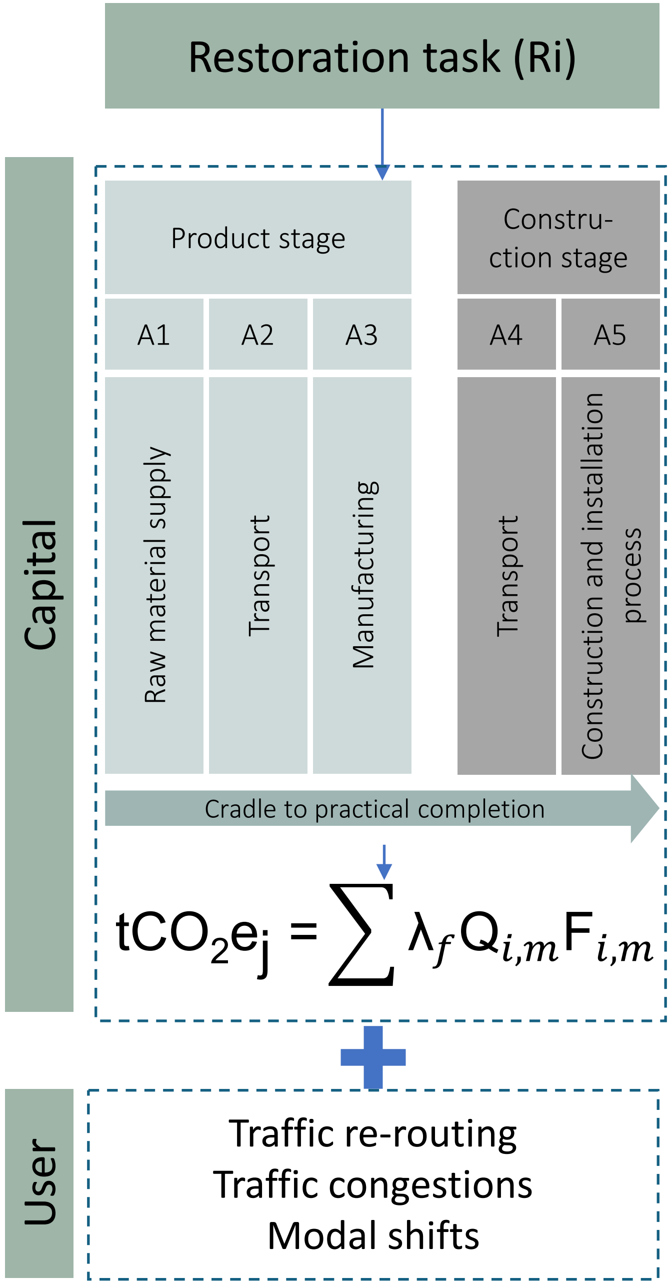
- The global warming potential (GWP) in tCO_2e
- λ_f - scalar factor for task duration, Q – quantity, F – carbon factor
- Biogenic and land use emissions are generally less than 5 % of GWP total – not included
- Two main emission groups:
  - capital/upfront emissions - construction works included in the restoration tasks (here A1-A5 cradle to practical completion)
  - user/ancillary emissions - traffic re-routing, pavement degradation
- Functional/equivalent unit: restoration task
- Life cycle inventory (UK data and literature)



Life cycle inventory

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 avg	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/m^3
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

Further details in Table A1 in Mitoulis et al. (2023)

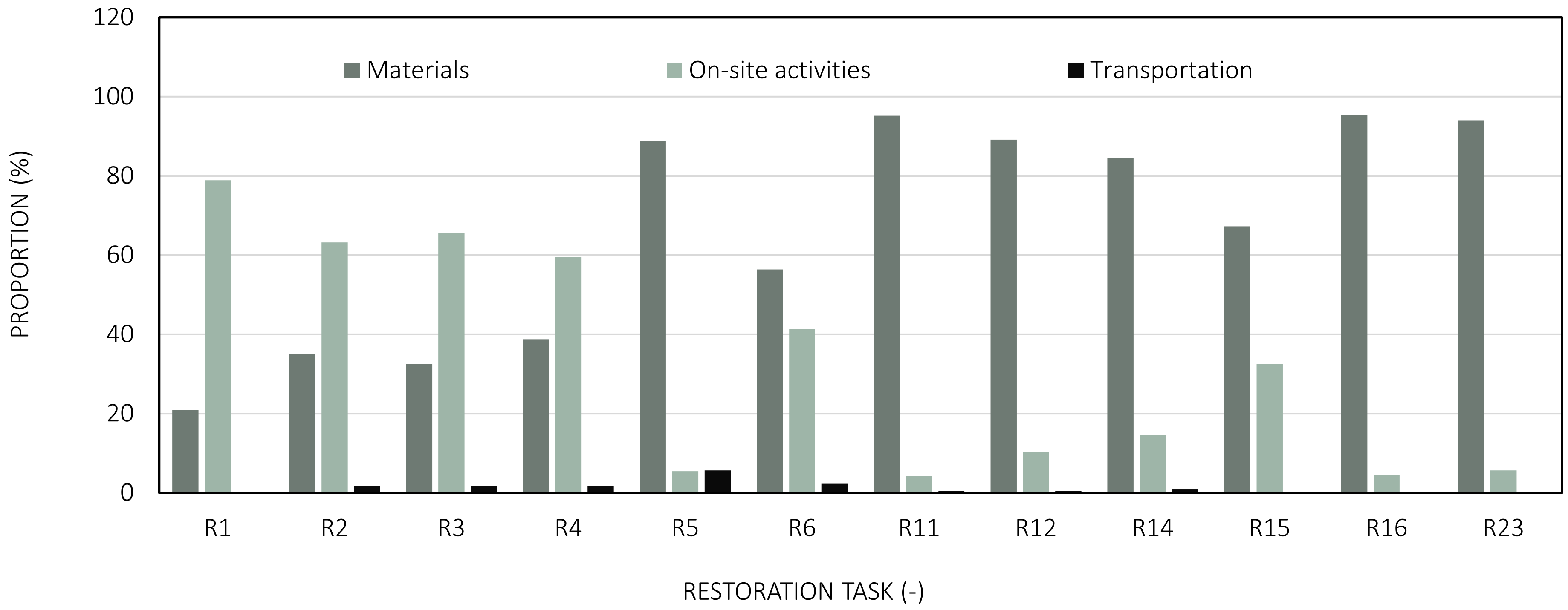


Assessment results

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 [3]

Assessment results



- The materials represent 21%-99% of the total emissions of the task (average 74%).
- On-site activities represent 2%-100% of the total emissions,
- Transportation <6% of the total emissions

Industry case studies: development of baselines

- Balfour Beatty Rail was responsible for **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.
- An **initial baseline** was calculated using high-level data from the tendering process, which revealed data gaps, particularly in certain work packages.
- A **workshop** with the client, design, and construction teams was held to improve data accuracy and raise awareness of carbon management. A follow-up meeting chaired by the Project Director assigned responsibility for data provision.
- **Material data** was derived from outline designs for each work package. Energy usage in the first two years was normalized and applied to the remaining work. The **Rail Industry Carbon Tool** was used to calculate the carbon baseline, ensuring transparency and traceability.
- **Effective planning** of baseline calculations and **early buy-in** from key individuals are essential for accurate baseline calculations and successful carbon management throughout the project.

Industry case studies: carbon emissions quantification

- WSP-Parsons Brinckerhoff Rail and Atkins served as the Lead Design Organization (LDO) for the **Network Rail's electrification program** from London to Oxford, Bristol, and South Wales.
- **Carbon reduction study** conducted at the Detailed Design stage focusing on embodied carbon in construction materials.
- Covered **embodied carbon for Route Sections** under LDO responsibility, and transportation and construction emissions were calculated by other contractors.
- Carbon Hotspots identified through **RSSB Tool outputs**, and reduction Opportunities were identified through
  - Reducing Material Quantity: **pile depth reduction** and associated carbon savings estimated, and thinner OLE mast option introduced to reduce steel and carbon emissions.
  - Changing Material Specification: using **concrete** mixes with **higher levels of GGBS** to reduce carbon, and limited opportunity to use reclaimed steel or low-carbon steel due to prior procurement.

Industry case studies: target setting

- Allies and Morrison Architects, in collaboration with Arup, developed a **masterplan for Madinat Al Irfan**, a mixed-use city district near Muscat International Airport, Oman.
- Aimed to be a model of sustainable urban development, setting b**enchmarks for infrastructure and carbon reduction**.
- A study quantified emissions for the base case, identifying **major sources** as transport, energy, and potable water supply.
- Explicit **performance targets** were set for these systems through client-design team **workshops**, focusing on significant improvements beyond baseline conditions.
- Carbon emissions were not stated directly; instead, **proxies were used** to calculate the reductions.
- The target was to **reduce per km travel emissions** by encouraging walking and public transport over car use.
- **Results** indicate that:
  - Capital carbon emissions for the building and infrastructure are similar between the Irfan Case and the Base Case.
  - Forecast carbon emissions over 20 years for Madinat Al Irfan are 40% lower than the Base Case.
  - Forecast costs for the Irfan development over 20 years are reduced by 44% compared to the baseline.

Summary

- Selection of databases, life-cycle inventories and assessment steps
- Evaluation of upfront carbon for conventional and sustainable solutions
- Selected industry case studies for infrastructure carbon management