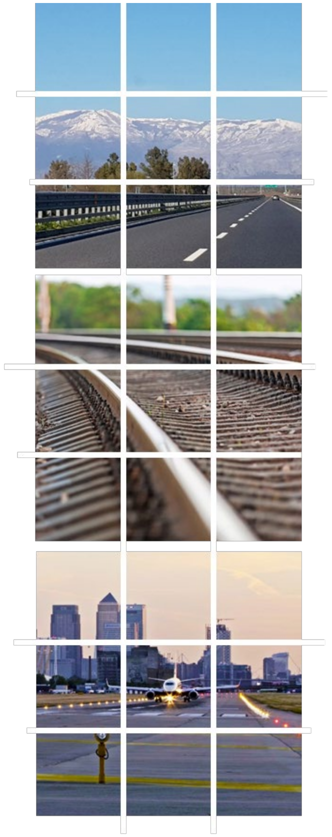
Transportation Infrastructures towards Green Transition



Life Cycle Assessment of road pavements and road infrastructures

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Lecture outline

- Overview of sustainability concepts
- Life Cycle Thinking
- Normative framework in sustainability assessment and LCA
- Overview of the LCA methodology
- Case study in asphalt pavement LCA
- Case study of On-Road Dynamic Charging Infrastructure
- Case study of a Concrete Bridge in Florida

Sustainability

Short overview

Sustainable development: point of origin

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:

- the concept of **needs**, in particular the essential needs of the world's poor, to which overriding priority should be given; and
- the idea of **limitations** imposed by the state of technology and social organization on the environment's ability to meet present and future needs.“

[World Commission on Environment and Development (WCED). *Our common future.* Oxford: Oxford University Press, 1987 p. 43. – also known as Brundtland Report]

GRO HARLEM BRUNDTLAND (NORWAY)
VICE CHAIR OF THE UN FOUNDATION BOARD OF DIRECTORS; FORMER PRIME MINISTER, NORWAY

Sustainable development: the role of United Nations

1987
Bruntland Report "Our Common Future"; UN World Commission on Environment and Development

1992
Earth Summit in Rio; Commission on Sustainable Development CSD;
Agenda 21

1995
Workshop on indicators of sustainable development for decision-making; CSD

1996
Indicators of sustainable development framework and Methodologies; CSD

2001
8 millennium development goals (MDGs), to be achieved by 2015; UN

2002
Earth Summit, South Africa

2012
World Summit in Rio; 'Open Working Group' to develop SDGs post-2015

2015
17 SDGs; "Transforming our world: the 2030 Agenda for sustainable development." Resolution adopted by the general assembly on 25 September 2015; UN

Sustainability and sustainable development: many definitions and one complex concept

- "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (Bruntland report, 1987)
- "Sustainability: the integration of environmental health, social equity and economic vitality in order to create thriving, healthy, diverse and resilient communities for this generation and generations to come. The practice of sustainability recognizes how these issues are interconnected and requires a systems approach and an acknowledgement of complexity." https://www.sustain.ucla.edu/what-is-sustainability/
- "Sustainability is based on a simple principle: Everything that we need for our survival and well-being depends, either directly or indirectly, on our natural environment. To pursue sustainability is to create and maintain the conditions under which humans and nature can exist in productive harmony to support present and future generations." https://www.epa.gov/sustainability/learn-about-sustainability#what

First time of three circles diagram: 1987

Sustainable economic development maximizes the goals across the biological and resource system (BS), the economic system (ES), and the social system (SS), as illustrated by the shaded area. In contrast, conventional development approaches maximize only ES goals, and Marxist economics maximizes only ES and SS goals.

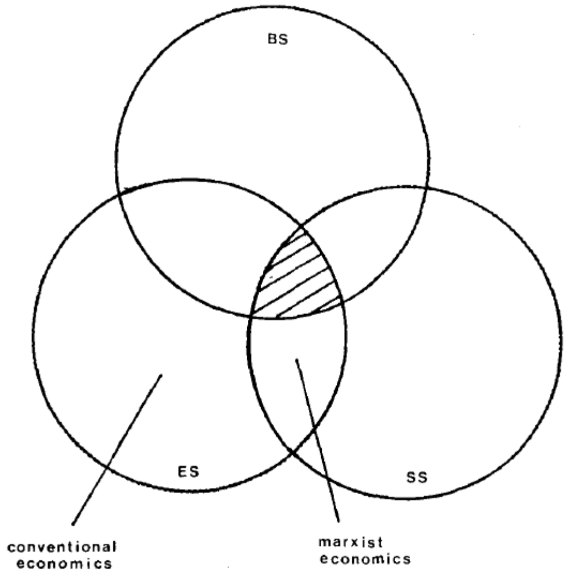
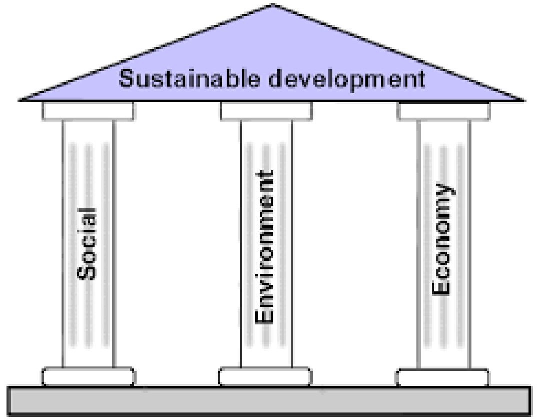
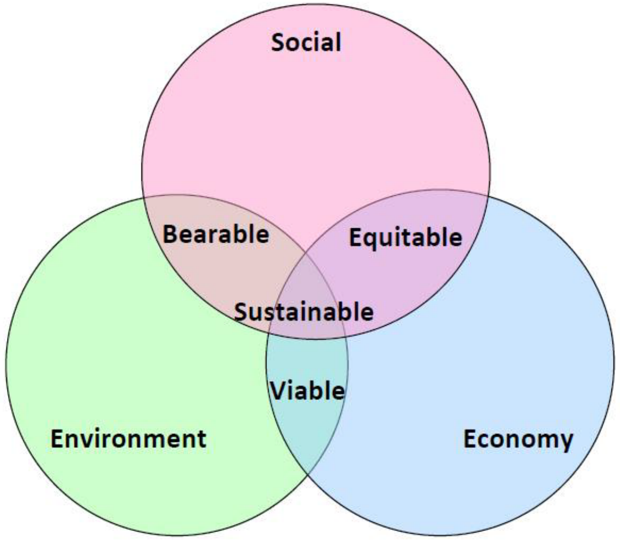


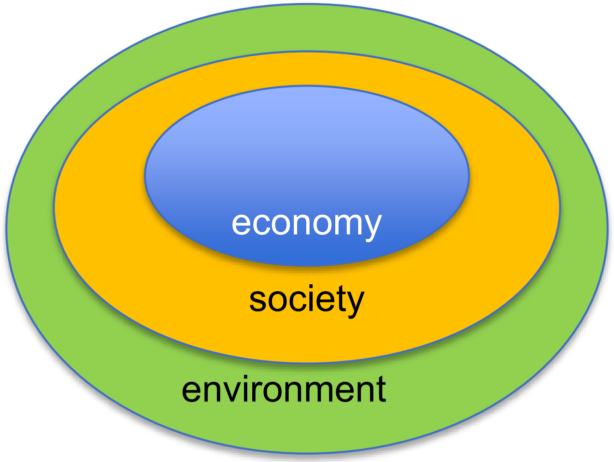
FIG. 1. *Sustainable economic development maximizes the goals across the biological and resource system (BS), the economic system (ES), and the social system (SS), as illustrated by the shaded area. In contrast, conventional development approaches maximize only ES goals, and Marxist economics maximizes only ES and SS goals.*

Barbier, E. (1987). The Concept of Sustainable Economic Development. Environmental Conservation, 14(2), 101-110. doi:10.1017/S0376892900011449

Three pillars of sustainability







"One particularly prevalent description of 'sustainability' employs three interconnected 'pillars'… encompassing economic, social, and environmental (or ecological) factors or 'goals'." [Purvis et al.]

Purvis, B., Mao, Y. & Robinson, D. Three pillars of sustainability: in search of conceptual origins. *Sustain Sci* **14,** 681–695 (2019). https://doi.org/10.1007/s11625-018-0627-5

2030 Agenda for Sustainable Development

- *The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, provides a shared blueprint for peace and prosperity for people and the planet, now and into the future. At its heart are the 17 Sustainable Development Goals (SDGs), which are an urgent call for action by all countries - developed and developing - in a global partnership. They recognize that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve our oceans and forests.*
- *The SDGs build on decades of work by countries and the UN, including the UN Department of Economic and Social Affairs*

GOALS FOR THE FUTURE

SUSTAINABLE DEVELOPMENT GOALS

SDG11-Sustainable cities and communities

Target

11.2

By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons

Indicators

11.2.1

Proportion of population that has convenient access to public transport, by sex, age and persons with disabilities

THE SUSTAINABLE DEVELOPMENT GOALS REPORT 2023: SPECIAL EDITION- UNSTATS.UN.ORG/SDGS/REPORT/2023/

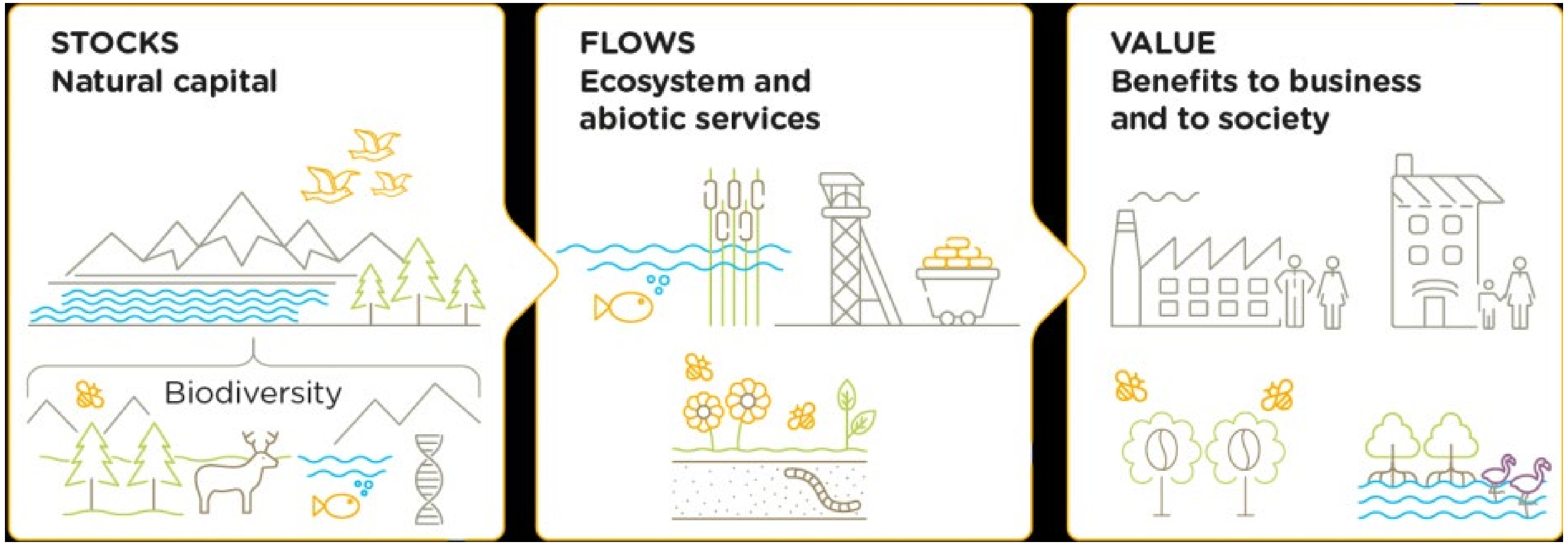
https://sdgs.un.org/

Sustainability principles by EU (COM/2020/98 final)

- improving product **durability, reusability, upgradability and reparability**, addressing the presence of hazardous chemicals in products, and increasing their energy and resource efficiency;
- increasing **recycled content** in products, while ensuring their performance and safety;
- enabling remanufacturing and high-quality recycling;
- reducing **carbon and environmental footprints**;
- restricting single-use and countering premature obsolescence;
- introducing a ban on the destruction of unsold durable goods;
- incentivising product-as-a-service or other models where producers keep the ownership of the product or the responsibility for its performance throughout its lifecycle;
- mobilising the potential of digitalisation of product information, including solutions such as digital passports, tagging and watermarks;
- rewarding products based on their different sustainability performance, including by linking high performance levels to incentives.

Natural Capital

"Natural capital is defined as a set of complex systems, consisting of evolving biotic and abiotic elements, that interact to determine the capacity of an ecosystem to directly and/or indirectly provide human society with a wide array of functions and services " [Pelenc et Ballet, 2015]



Pelenc, J., Ballet, J. Strong sustainability, critical natural capital and the capability approach, Ecological Economics, 112, 2015, 36-44, https://doi.org/10.1016/j.ecolecon.2015.02.006.

https://capitalscoalition.org/guide_supplement/biodiversity-4/

Weak sustainability

- Natural capital and manufactured capital are essentially substitutable
- There are no essential differences between the kinds of well-being they produce
- The only thing that matters is the total value of the aggregate stock of capital, which should be at least maintained, or ideally added to, for the sake of future generations
- This approach implies that the degradation of natural capital can be compensated by the estimated equivalent amount of manufactured or financial capital.
- Technological progress is assumed to constantly generate technical solutions to the environmental problems that are caused by the increased production of goods and services

Pelenc, J., Ballet, J. Strong sustainability, critical natural capital and the capability approach, Ecological Economics, 112, 2015, 36-44, https://doi.org/10.1016/j.ecolecon.2015.02.006.

Strong sustainability

- There is a qualitative difference between manufactured capital and natural capital
- Natural capital is irreversible and subject to the threshold phenomenon
- The amount of manufactured capital can be increased or decreased, while natural capital can disappear under severe conditions
- Manufactured capital requires natural capital for its production, so manufactured capital cannot be a complete substitute for natural capital

Pelenc, J., Ballet, J. Strong sustainability, critical natural capital and the capability approach, Ecological Economics, 112, 2015, 36-44, https://doi.org/10.1016/j.ecolecon.2015.02.006.

Strong sustainability

- Natural capital is multifunctional, providing a number of benefits at the same time
- The effects on human being of destroying the natural capital are unknown
- An increase in future consumption is not an appropriate substitute for the loss of natural capital
- "The substitutability between natural capital and other forms of capital should be strictly limited to the circumstances where the use of the services provided by natural capital does not lead to the irreversible destruction of this capital because its depletion cannot be compensated for by investing in other forms of capital" [Neumayer, 2012]

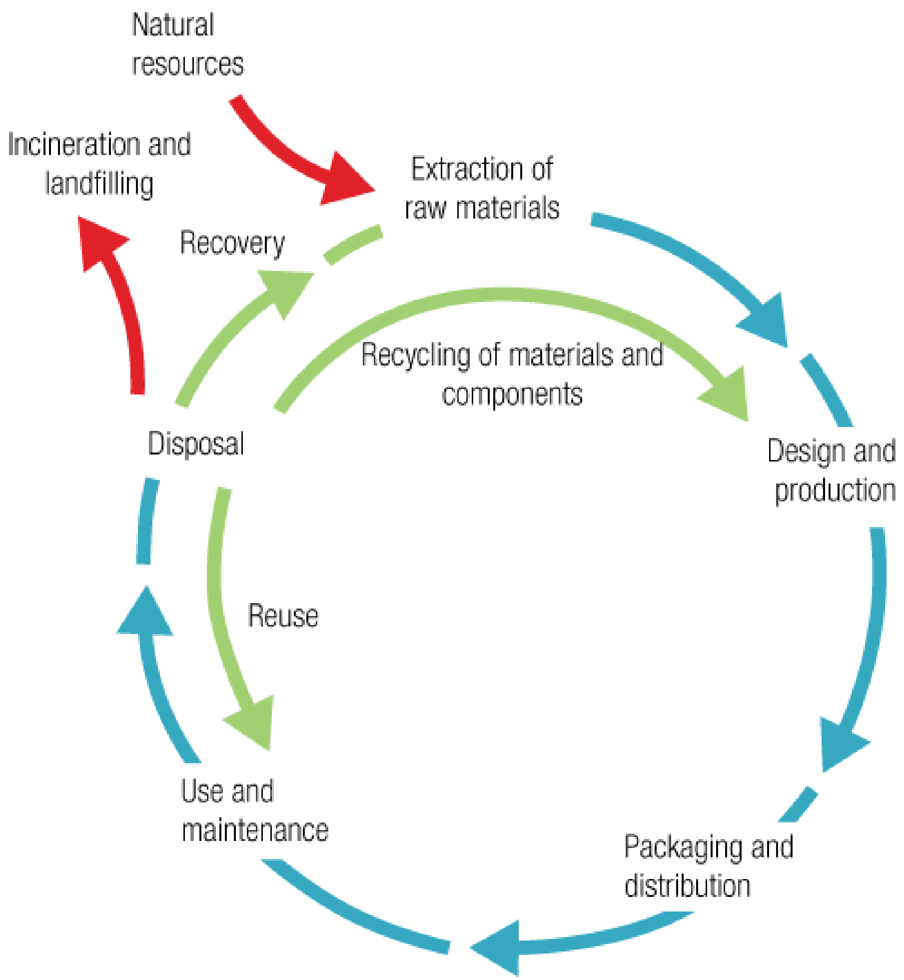
Pelenc, J., Ballet, J. Strong sustainability, critical natural capital and the capability approach, Ecological Economics, 112, 2015, 36-44, https://doi.org/10.1016/j.ecolecon.2015.02.006.
Eric Neumayer (2012) Human Development and Sustainability, Journal of Human Development and Capabilities, 13:4, 561-579, DOI: 10.1080/19452829.2012.693067

Life Cycle Thinking (LCT)

A mental approach to life

Life Cycle Thinking

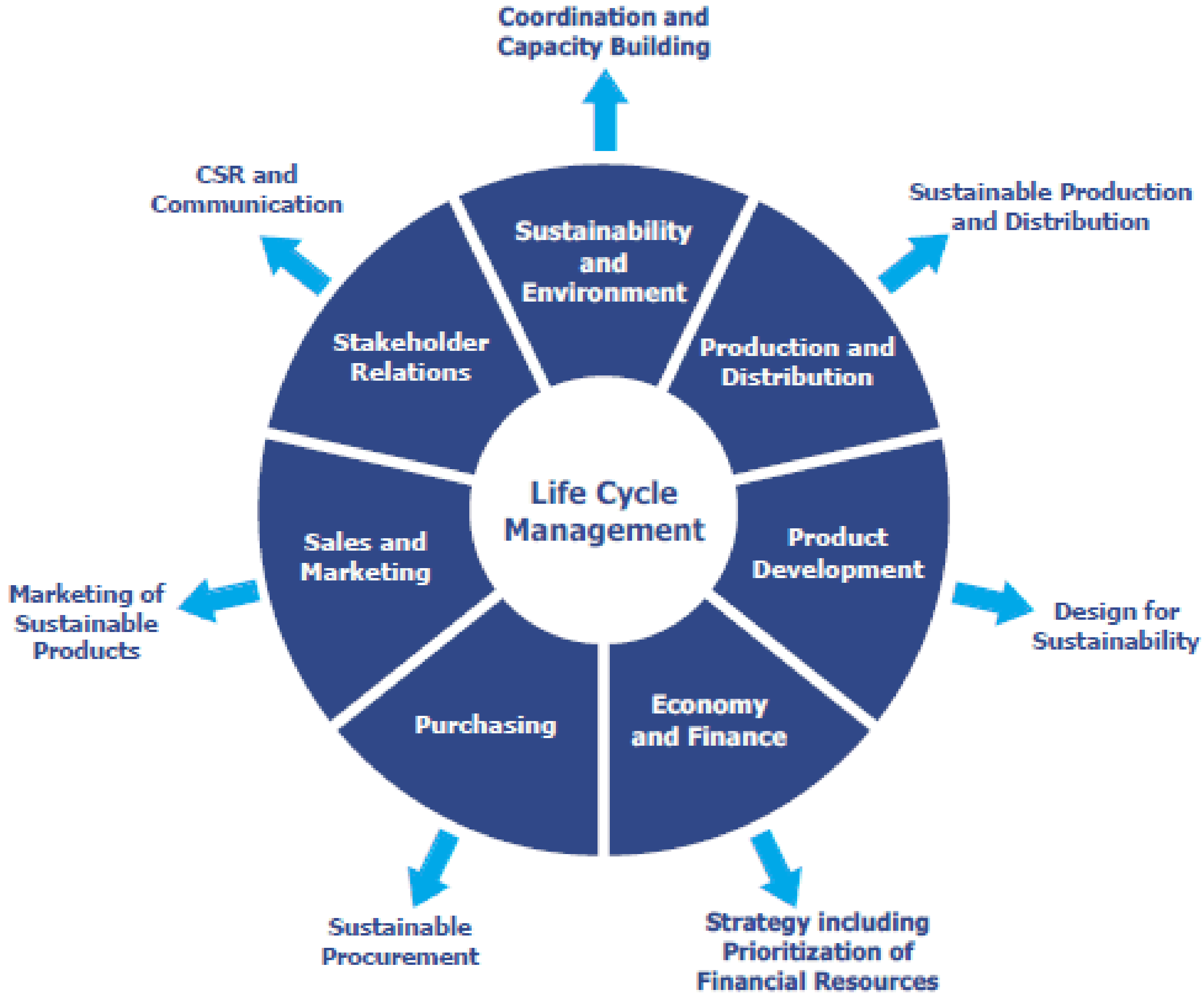
Life Cycle Thinking (LCT) is about going beyond the traditional focus on production site and manufacturing processes to include environmental, social and economic impacts of a product over its entire life cycle.



https://www.lifecycleinitiative.org/starting-life-cycle-thinking/what-is-life-cycle-thinking/

Life Cycle Management (LCM)

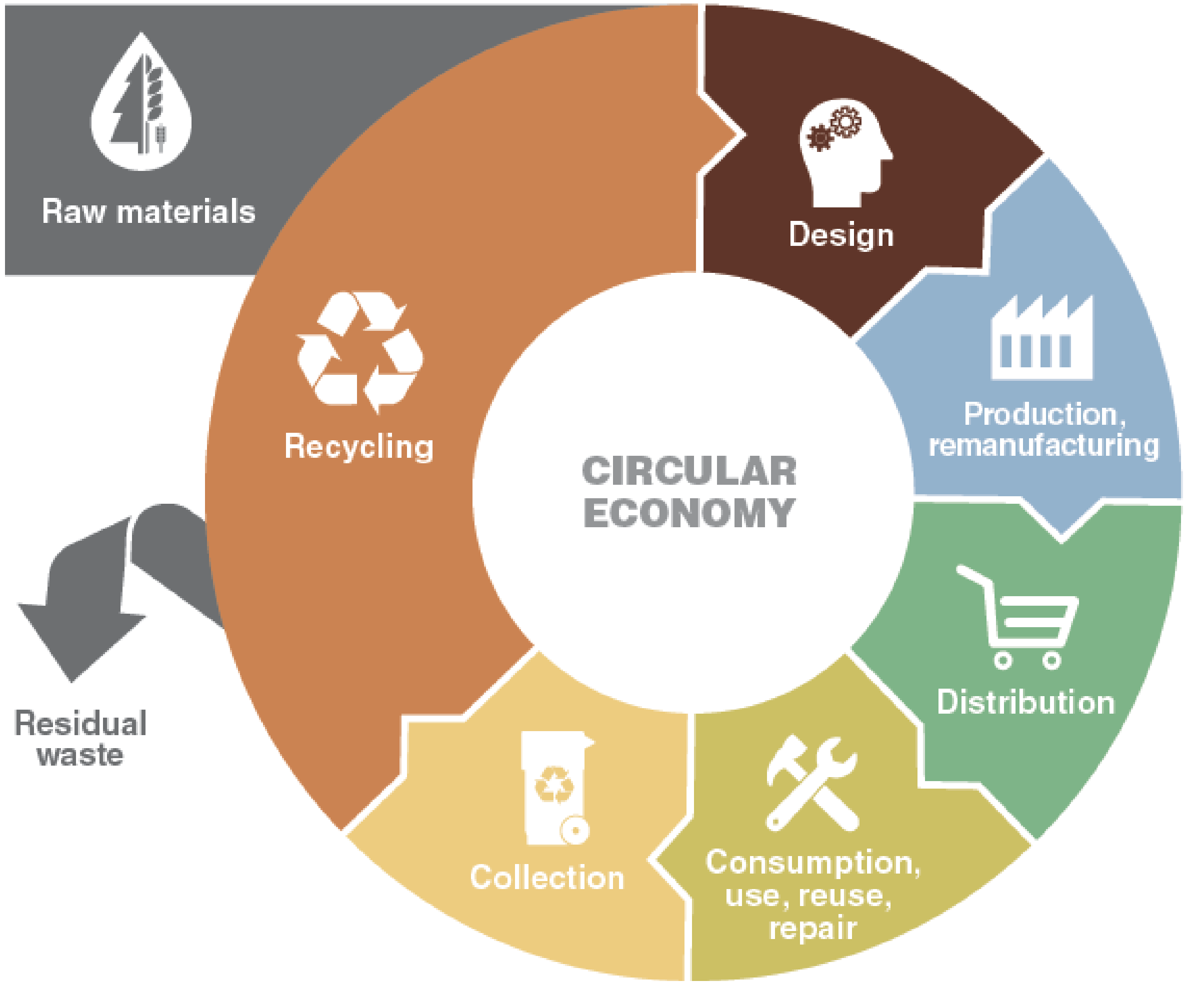
Life Cycle Management is the way to make operational LCT



https://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/

Circular economy

Circular economy: an economic model based inter alia on sharing, leasing, reuse, repair, refurbishment and recycling, in an (almost) closed loop, which aims to retain the highest utility and value of products, components and materials at all times.



https://www.europarl.europa.eu/RegData/etudes/BRIE/2016/573899/EPRS_BRI%282016%29573899_EN.pdf

Life Cycle Sustainability Assessment (LCSA): a quantitative methodology to assess sustainability throughout the entire life cycle

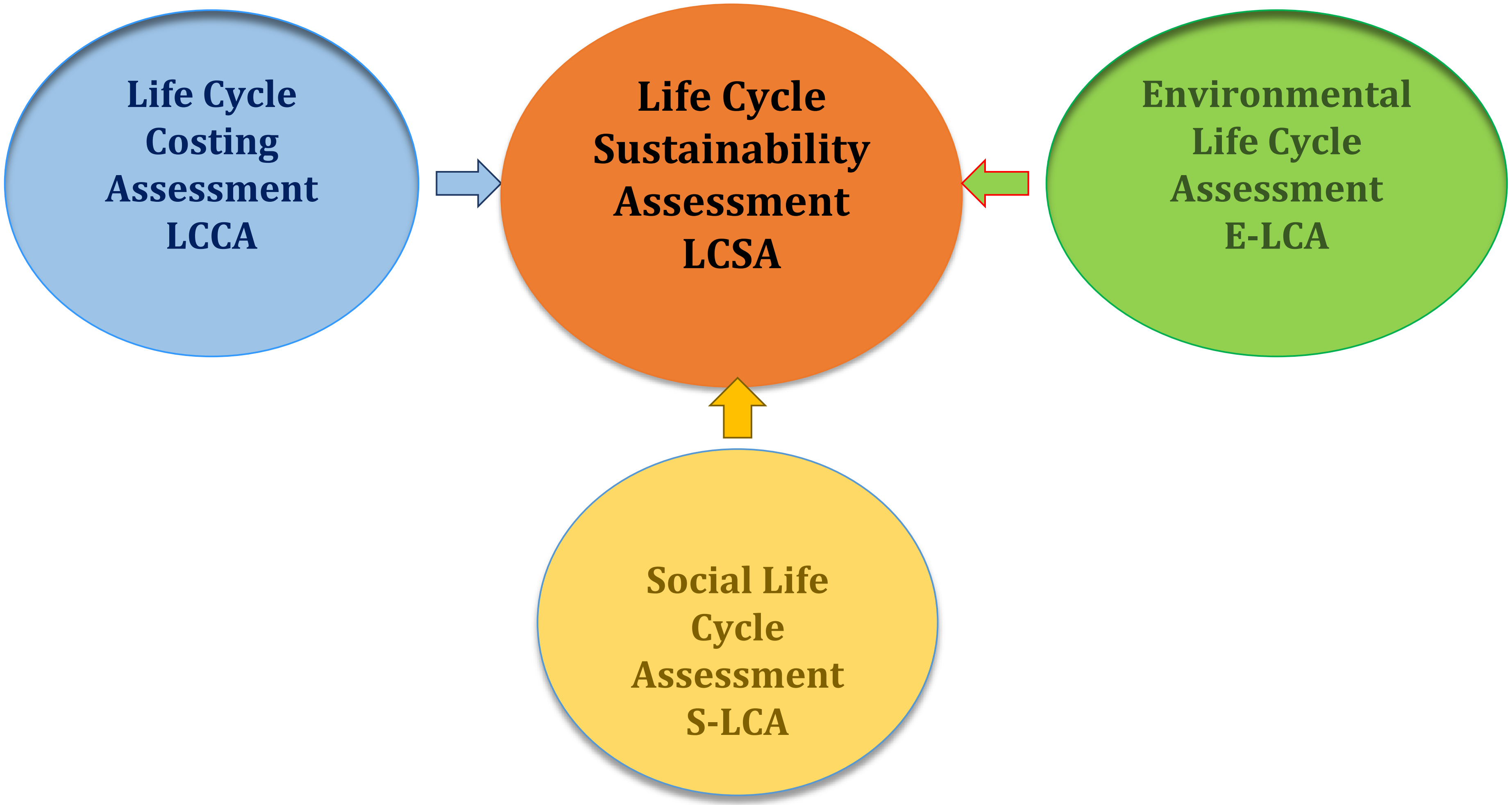
Life Cycle Sustainability Assessment (LCSA) refers to the evaluation of all environmental, social and economic negative impacts and benefits in decision-making processes towards more sustainable products throughout their life cycle.

To achieve the quantitative assessment there are three methodologies:

- Environmental Life Cycle Assessment (E-LCA)
- Life Cycle Cost Assessment (LCCA) or Life Cycle Costing (LCC)
- Social Life Cycle Assessment (S-LCA)

https://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/life-cycle-sustainability-assessment/

Sustainability Assessment from a life cycle perspective



Normative frameworks

Standard for sustainability assessment and life cycle assessment

Standards for life cycle sustainability assessment

E-LCA

- EN ISO 14040:2006+A1:2020 - Environmental management — Life cycle assessment — Principles and framework
- EN ISO 14044:2006+A2:2020 - Environmental management — Life cycle assessment — Requirements and guidelines

LCCA

- ISO 15686-5:2017 - Buildings and constructed assets. Service life planning. Life-cycle costing

S-LCA

- Guidelines for S-LCA of Products and Organizations 2020 - UN
- Under development ISO/CD 14075 - Principles and framework for social life cycle assessment

https://www.lifecycleinitiative.org/library/guidelines-for-social-life-cycle-assessment-of-products-and-organisations-2020/

Standards for urban sustainability assessment

Sustainable cities

- ISO 37120:2018 - Sustainable cities and communities - Indicators for city services and quality of life
- PAS 2070:2013 Incorporating Amendment No.1 - Specification for the assessment of greenhouse gas emissions of a city - Direct plus supply chain and consumption-based methodologies

Smart cities

- ISO 37122:2019 - Sustainable cities and communities - Indicators for smart cities

Resilient cities

- ISO 37123:2019 - Sustainable cities and communities - Indicators for smart cities

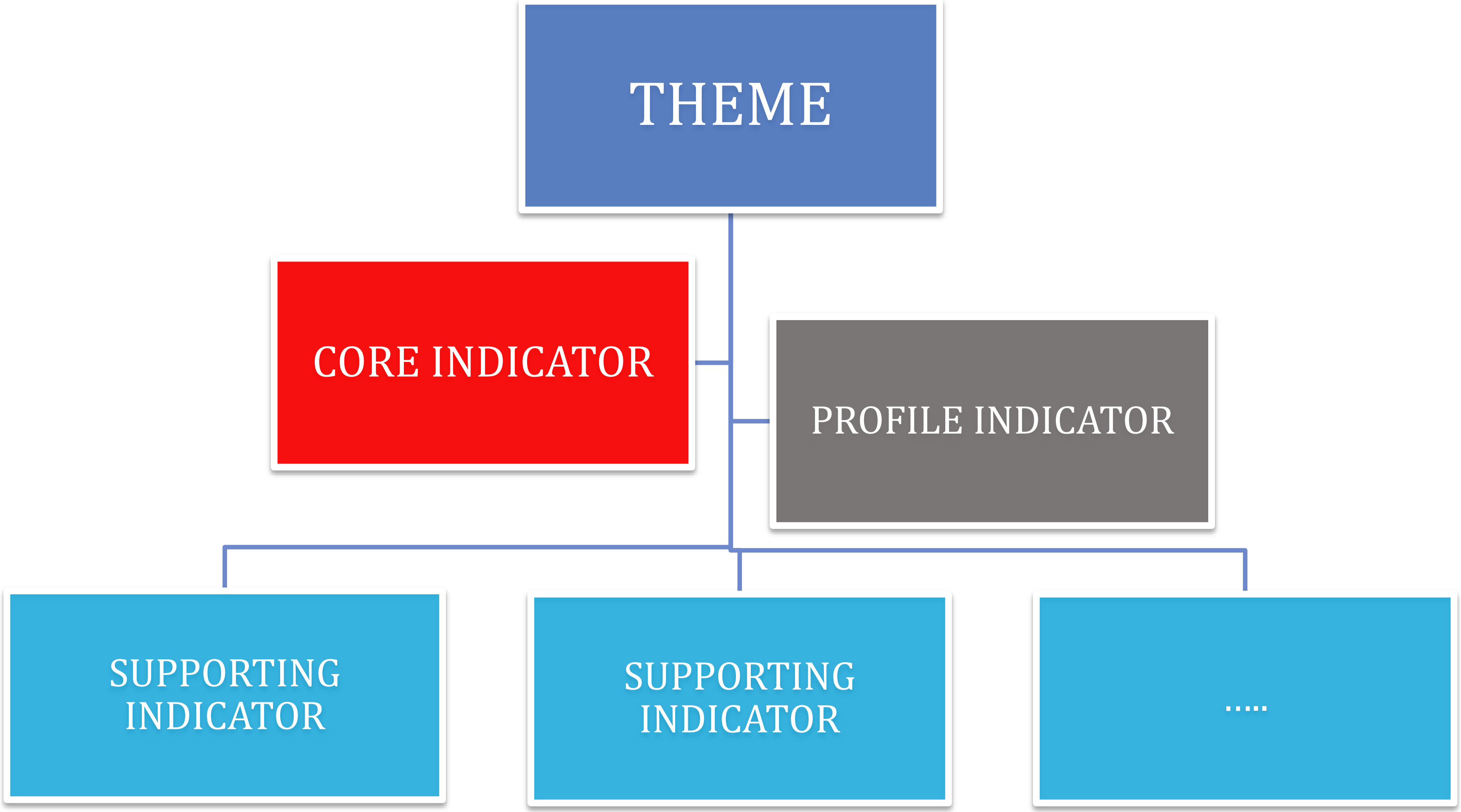
Smart & Resilient Cities

- A smart city is a place where traditional networks and services are made more efficient with the use of digital and telecommunication technologies for the benefit of its inhabitants and business.
- A smart city goes beyond the use of information and communication technologies (ICT) for better resource use and less emissions. It means smarter urban transport networks, upgraded water supply and waste disposal facilities and more efficient ways to light and heat buildings. It also means a more interactive and responsive city administration, safer public spaces and meeting the needs of an ageing population. (https://ec.europa.eu/info/eu-regional-and-urban-development/topics/cities-and-urban-development/city-initiatives/smart-cities_en)
- Resilient cities are cities that have the ability to absorb, recover and prepare for future shocks (economic, environmental, social & institutional). Resilient cities promote sustainable development, well-being and inclusive growth. (https://www.oecd.org)

ISO 37120:2018 - Themes

1. ECONOMY
2. EDUCATION
3. ENERGY
4. ENVIRONMENT AND CLIMATE CHANGE
5. FINANCE
6. GOVERNANCE
7. HEALTH
8. HOUSING
9. POPULATION AND SOCIAL CONDITION
10. RECREATION
11. SAFETY
12. SOLID WASTE
13. SPORT AND CULTURE
14. TELECOMMUNICATION
15. TRANSPORTATION
16. URBAN/LOCAL AGRICULTURE AND FOOD SECURITY
17. URBAN PLANNING
18. WASTEWATER
19. WATER

Types of indicators



Transportation

TRANSPORTATION

- kilometres of public transport system per 100 000 population
- Annual number of public transport trips per capita
- Number of personal automobiles per capita
- Number of two-wheeled motorized vehicles per capita
- Percentage of commuters using a travel mode to work other than a personal vehicle
- kilometres of bicycle paths and lanes per 100 000 population
- Transportation deaths per 100 000 population
- Percentage of population living within 0,5 km of public transit running at least every 20 min during peak periods
- Average commute time

EN standards for construction works

EUROPEAN STANDARDS

EN 15804:2012+A2:2019 – PRODUCT LEVEL

Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products

EN 15978:2011 – BUILDING LEVEL

Sustainability of construction works — Assessment of environmental performance of buildings — Calculation method

EN 15643:2021 – Sustainability of construction works — Framework for assessment of buildings and civil engineering works

ISO standards for construction works

EUROPEAN STANDARDS

ISO 21930:2017 – PRODUCT LEVEL

Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services

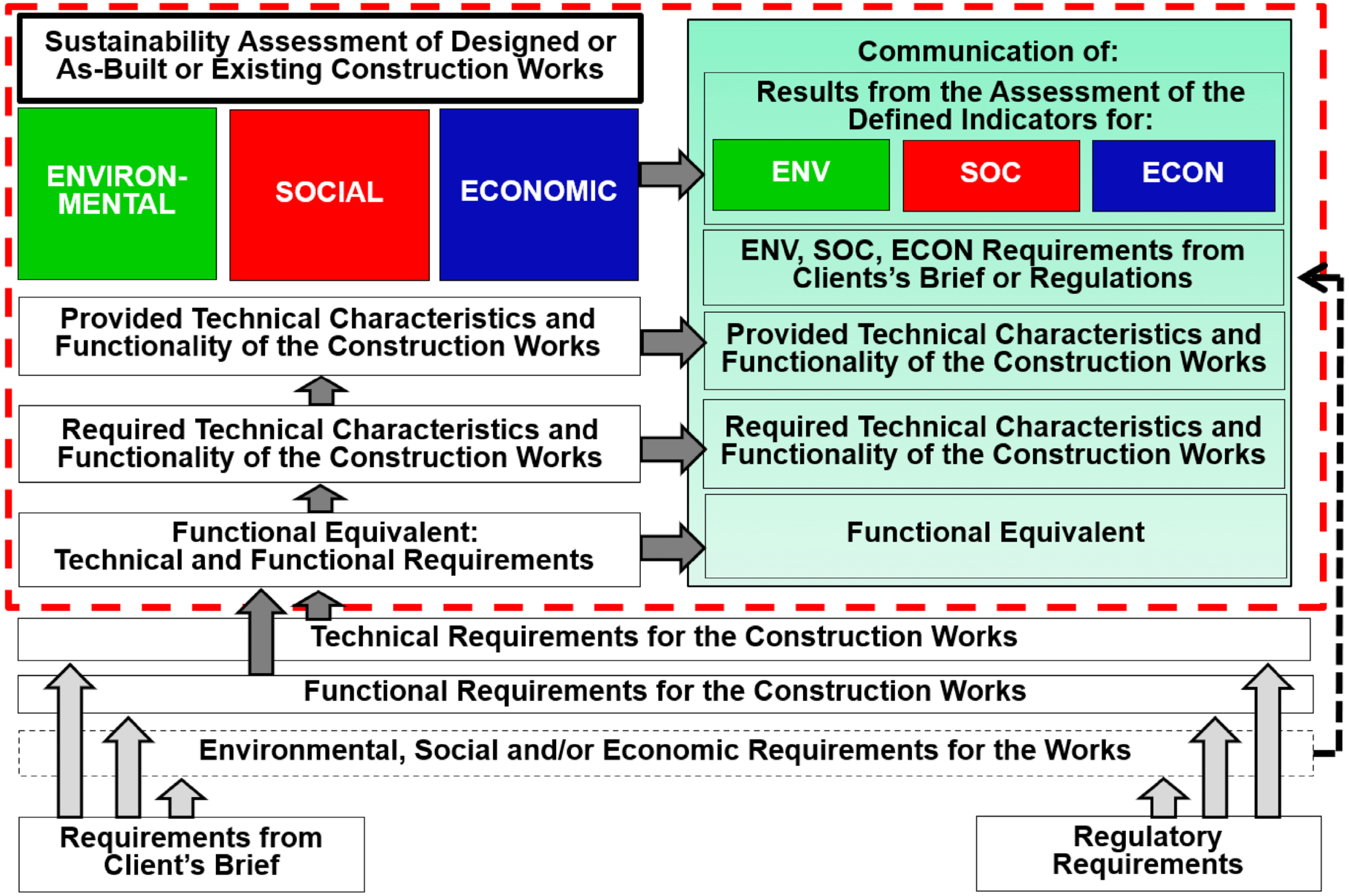
ISO 21931-1:2022 – BUILDING LEVEL

Sustainability in buildings and civil engineering works — Framework for methods of assessment of the environmental, social and economic performance of construction works as a basis for sustainability assessment - Part 1: Buildings

ISO 21931-2:2019 – CIVIL ENGENEERING WORKS

Sustainability in buildings and civil engineering works — Framework for methods of assessment of the environmental, social and economic performance of construction works as a basis for sustainability assessment - Part 2: Civil engineering works

Framework for sustainability assessment of construction works



EN 15643:2021

Environmental labels

- **environmental label or environmental declaration:** *claim which indicates the environmental aspects of a product or service*
- *An environmental label or declaration may take the form of a statement, symbol or graphic on a product or package label, in product literature, in technical bulletins, in advertising or in publicity, amongst other things.*
- **environmental aspect:** *element of an organization's activities, products or services which can interact with the environment*

Standards ISO

ISO 14020:2001 Environmental labels and declarations — General principles

- EN ISO 14021:2016 Environmental labels and declarations - Self-declared environmental claims (Type II environmental labelling)
- EN ISO 14024:2018 Environmental labels and declarations - Type I environmental labelling - Principles and procedures
- EN ISO 14025:2010 Environmental labels and declarations - Type III environmental declarations - Principles and procedures

Environmental Product Declaration (EPD)

Product Category Rule (PCR)

set of specific rules, requirements and guidelines for developing Type III environmental declarations for one or more product categories

Life Cycle Assessment (LCA)

compliant with ISO 14040 & ISO 14044 and performed in accordance with specific PCR

Environmental Product Declaration (EPD)

Type III label

public document summarising the environmental performances results

Product Category Rules

product category rules (PCR) *are a set of specific rules, requirements and guidelines for developing Type III environmental declarations for one or more product categories*

- PCR define how to perform an LCA study of a product;
- PCR for construction products are contained in the European standard EN 15804 or ISO 21930
- Certified LCAs of products are found as EPDs
- A programme operator is a body or bodies that conduct a Type III environmental declaration programme
- A program operator can be a company or a group of companies, industrial sector or trade association, public authorities or agencies, or an independent scientific body or other organization

European Program Operators

- Institut Bauen und Umwelt e.V. (IBU) from Germany
- Inies FDES from France
- EPD Danmark from Denmark
- EPD Norge from Norway
- EPD Italy
- International EPD® System from Sweden
- BRE, from United Kingdom.
- Global EPD from Spain
- ITB-EPD from Poland
- Bau EPD from Austria
- DAP construccion from Spain
- EPD Italy from Italy
- DAPHabitat from Portugal
- ZAG EPD from Slovenia
- EPD Ireland, from Ireland
- MRPI, from the Netherlands
- PEP Eco passport

Program Operators

- https://aclca.org/pcr/program-operators/
- https://www.eco-platform.org/home.html (building sector)
- http://www.pep-ecopassport.org/

Introduction to environmental LCA

An overview of the methodology

Standards for Life Cycle Assessment (LCA)

- EN ISO 14040:2006+A1:2020 - Environmental management — Life cycle assessment — Principles and framework
- EN ISO 14044:2006+A2:2020 - Environmental management — Life cycle assessment — Requirements and guidelines
- ISO/TR 14047:2012 - Environmental management - Life cycle assessment - Illustrative examples on how to apply ISO 14044 to impact assessment situations - Second Edition
- ISO/TR 14049:2012 - Environmental management - Life cycle assessment - Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis
- CEN ISO/TS 14071:2016 - Environmental management — Life cycle assessment — Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006

Life Cycle Assessment (LCA): what

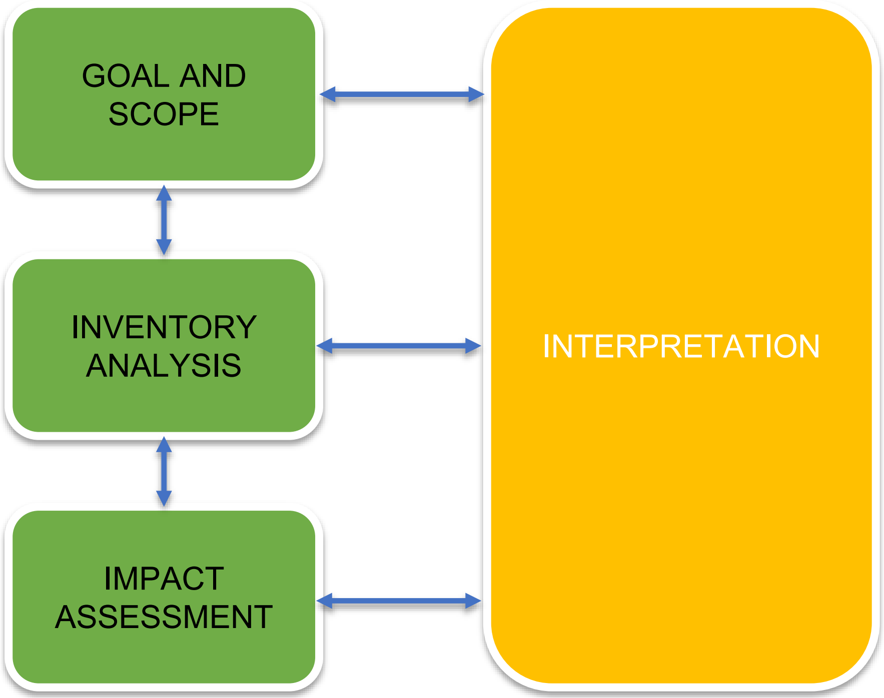
- LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave). [ISO 14040]

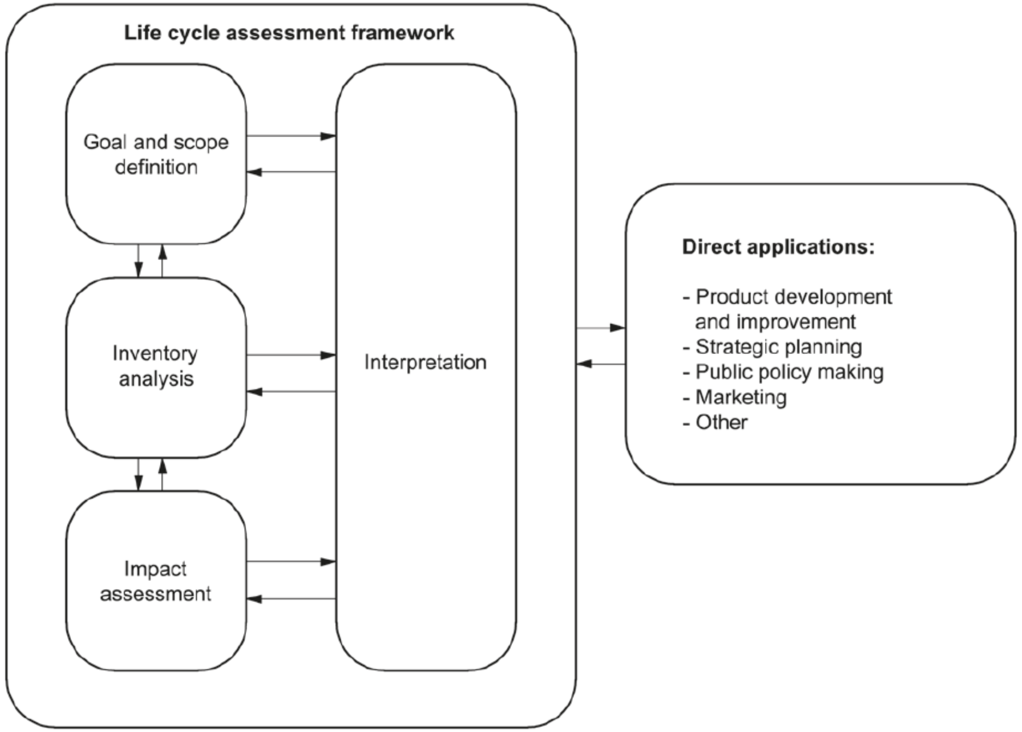
- And my personal definition:
- "LCA is a **quantitative** methodology which addresses the environmental aspects of a **product system** and estimates the potential environmental impacts) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)."

Life Cycle Assessment (LCA): why

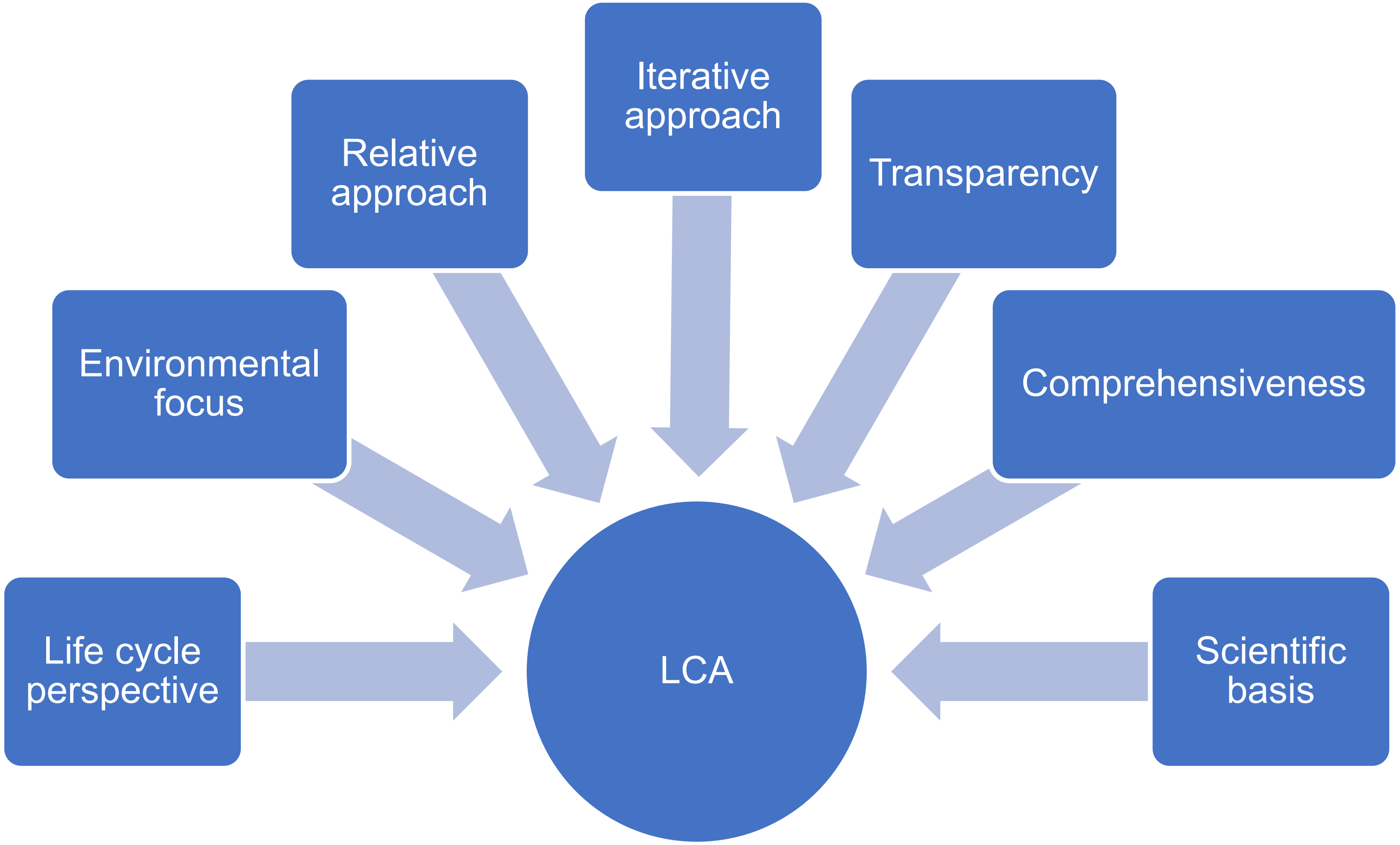
- identifying opportunities to improve the environmental performance of products at various points in their life cycle,
- informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign),
- the selection of relevant indicators of environmental performance, including measurement techniques,
- marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration).

Life Cycle Assessment (LCA): how





Life Cycle Assessment (LCA): features



Carbon and water footprint

- EN ISO 14067:2018 Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification
  - **The carbon footprint of a product (CFP)** is the sum of *GHG emissions* and *GHG removals* in a *product system*, expressed as *CO2 equivalents* and based on a *life cycle assessment* using the single *impact category* of climate change

- EN ISO 14046:2016 - Environmental management — Water footprint — Principles, requirements and guidelines
  - The water footprint is a metric that quantifies the potential environmental impacts related to water

GOAL: why

In this phase we answer **why** we are going to carry out an LCA study!

- the intended application
- the reasons for carrying out the study
- the intended audience, i.e. to whom the results of the study are intended to be communicated,
- whether the results are intended to be used in comparative assertions intended to be disclosed to the public.

SCOPE: what

- the product system to be studied;
- the functions of the product system or, in the case of comparative studies, the systems;
- the functional unit;
- the system boundary;
- allocation procedures;
- impact categories selected and methodology of impact assessment, and subsequent interpretation to be used;
- data requirements;
- assumptions;
- limitations;
- initial data quality requirements;
- type of critical review, if any;
- type and format of the report required for the study.

The product system

- The product system is the object being investigated in an LCA, but what is exactly meant by "**product system**"?
- Any of these can serve the function of product system:

❑ a product (i.e. a supercapacitor)

❑ a process (i.e. graphene production)

❑ a service (i.e. electrical energy delivery or passenger transportation)

- In other words a **human activity**!
- Natural occurring events are not considered in LCA!

Functional Unit (FU)

➢ **Functional unit vs reference flow**

- **functional unit**
  - quantified performance of a product system for use as a reference unit
- **reference flow**
  - measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit

How to find out the FU?

Once the system product has been chosen and properly defined, one has to ask himself these three questions:

- Which is the function of the product system relevant for our present study, i.e. strictly connected to the goal of the study?
- Which variable can quantitatively describe this function?
- What is the value of the selected variable which fulfils the aforementioned function?

ISO 21930:2017

Functional unit

- The functional unit defines the way in which the identified functions and performance characteristics of the product are quantified. The primary purpose of the functional unit is to provide a reference by which product, material and energy flows (input and output data) of a construction product's LCA results and any other information are normalized to produce data expressed on a common basis.

FU has to answer these questions:

"what",

"how much"

"how well"

"for how long"

- ISO 21930:2017 Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services

Declared Unit DU

- When the precise function of the product or scenarios at the construction works level is not stated, or is unknown, a declared unit may be used instead of the functional unit. The declared unit provides a reference by which product, material and energy flows (input and output data) of the information module of a construction product’s LCA results and any other information are normalized to produce data expressed on a common basis.

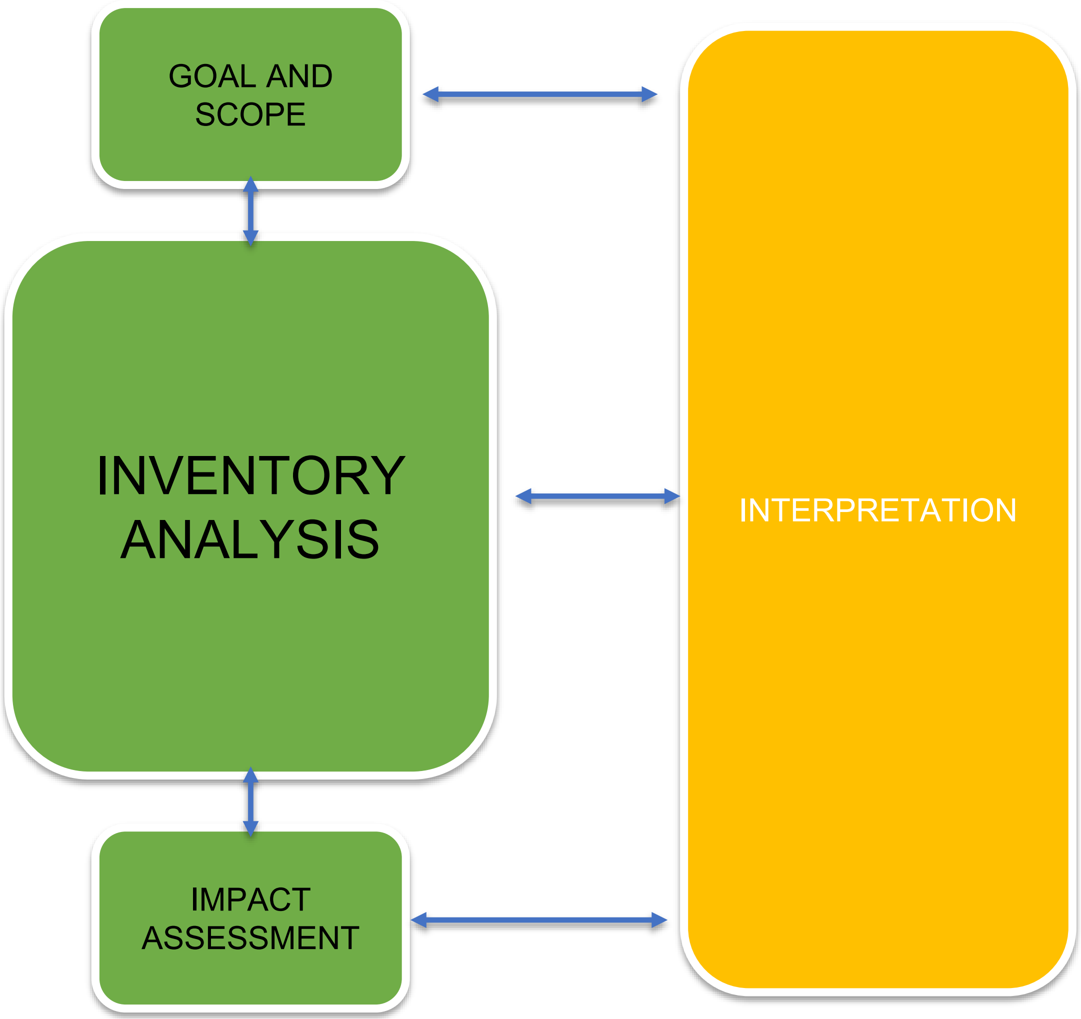
The concept of DU has pervaded any sector beyond the construction one!

- ISO 21930:2017 Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services

LCA stages for building and construction products (EN 15804)

Product stage			Con-struction stage		Use stage							End of Life stage				Benefits and loads beyond the system boundary
Raw material supply	Transport	Manufacturing	Transport to the site	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction 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

Inventory: second phase



Life Cycle Inventory analysis: LCI

- *phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle*
  - Mass and energy balance of the product system, i.e. calculation of all elementary flows and product flows crossing the system boundary
- *energy inputs, raw material inputs, ancillary inputs, other physical inputs,*
- *products, co-products and waste,*
- *emissions to air, discharges to water and soil, and*
- *other environmental aspects.*

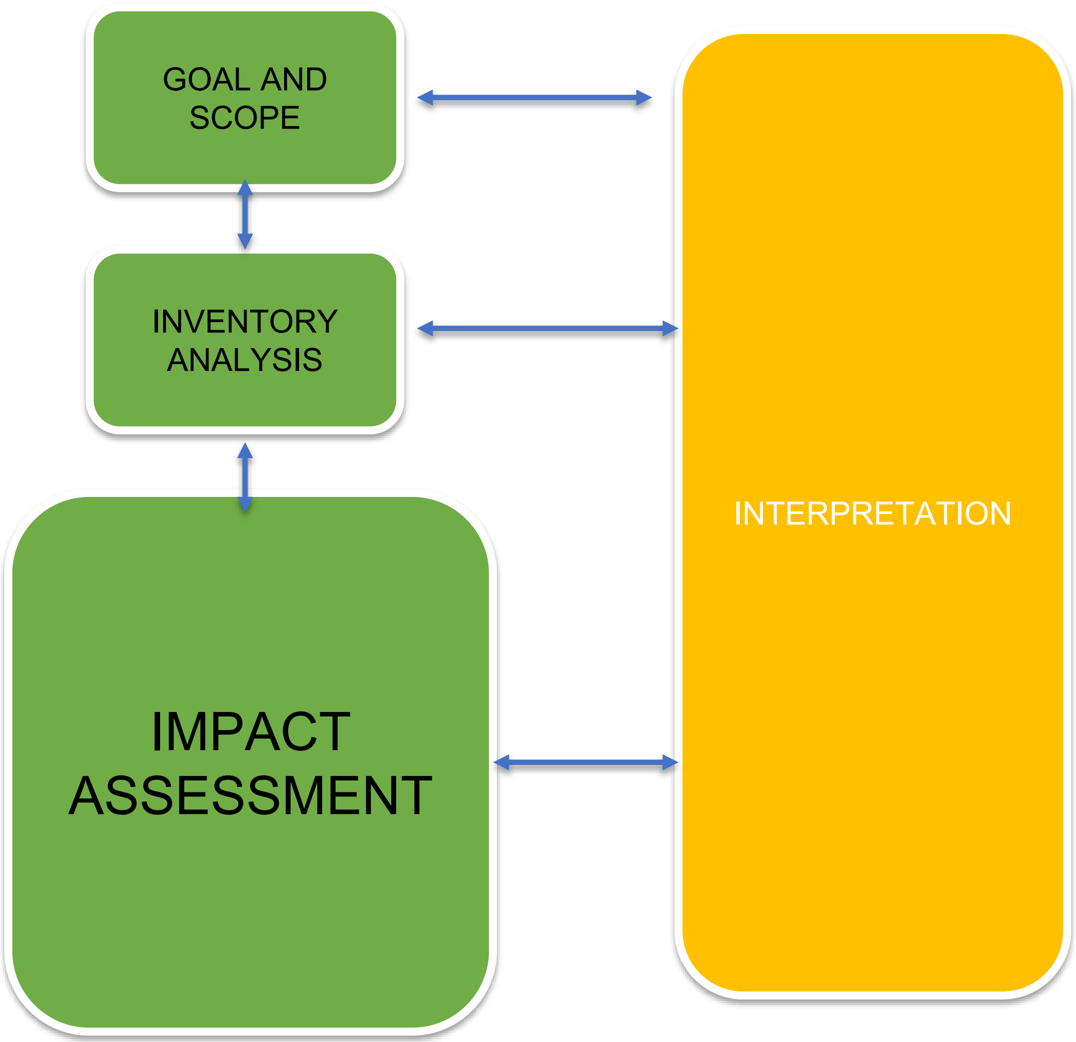
Life Cycle Inventory analysis: LCI

- Data collection
  - All input and output flows
  - all types of data

- Data calculation
  - Validation
  - Attribution to unit processes
  - Relation to the reference flow

Impact assessment: third phase

- phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product



Life Cycle Interpretation

- Interpretation is the phase of LCA in which the findings from the inventory analysis and the impact assessment are considered together or, in the case of LCI studies, the findings of the inventory analysis only.
- The interpretation phase should deliver results that are consistent with the defined goal and scope and which reach conclusions, explain limitations and provide recommendations.
- The interpretation should reflect the fact that the LCIA results are based on a relative approach, that they indicate potential environmental effects, and that they do not predict actual impacts on category endpoints, the exceeding of thresholds or safety margins or risks.

Case studies

Case study in asphalt pavement LCA

Case study of On-Road Dynamic Charging Infrastructure

Case study of a Concrete Bridge in Florida

Comparative life cycle assessment of asphalt pavements: goal

The first goal is the quantification of the environmental savings producing asphalt pavements with a major percentage of Reclaimed Asphalt Pavement (RAP) and using Warm Mix Asphalt (WMA).

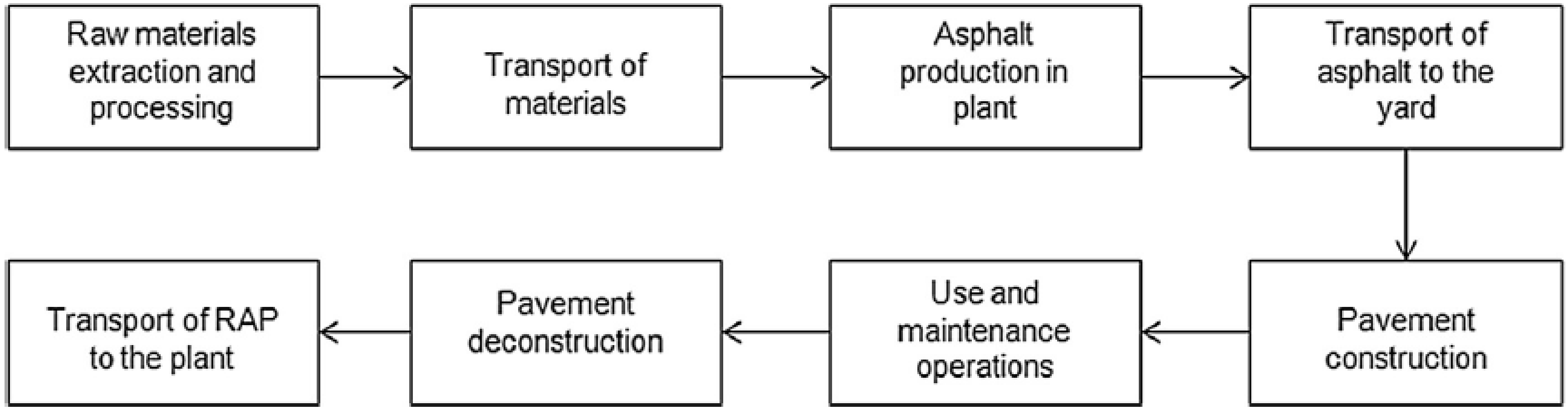
The second goal is to find out how much the rehabilitation of the base layer through Cold In-Place Recycling (CIR) technology can reduce energy consumption and emissions generation and conserve natural resources (aggregate and asphalt binder).

This work was out in collaboration with Impresa Bacchi S.r.l., a mid-size Italian asphalt-producing company.

M. Giani, G. Dotelli, N. Brandini, L. Zampori, Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling, Resources, Conservation and Recycling, Volume 104, Part A, 2015, pp. 224-238,https://doi.org/10.1016/j.re sconrec.2015.08.006.

Comparative life cycle assessment of asphalt pavements: scope

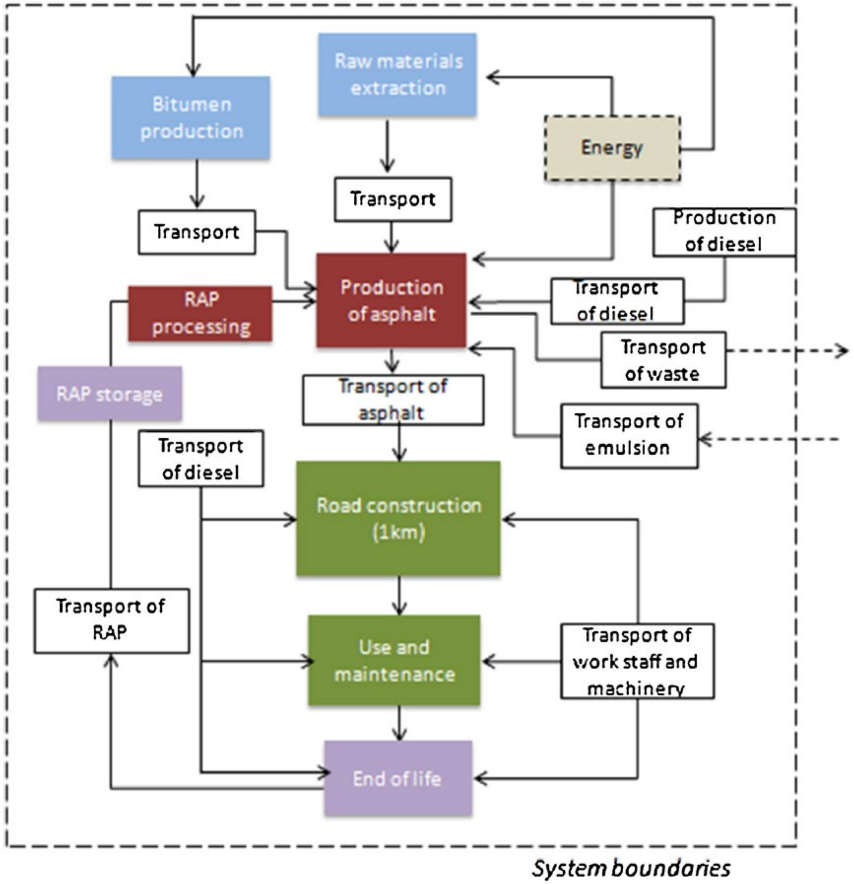
Product system: all processes needed to construct and maintain a typical asphalt road pavement in Italy: material production, pavement construction, pavement maintenance, deconstruction and recycling.



M. Giani, G. Dotelli, N. Brandini, L. Zampori, Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling, Resources, Conservation and Recycling, Volume 104, Part A, 2015, pp. 224-238,https://doi.org/10.1016/j.re sconrec.2015.08.006.

Comparative life cycle assessment of asphalt pavements: scope

System boundaries: all processes needed to construct and maintain a typical asphalt road pavement in Italy: material production, pavement construction, pavement maintenance, deconstruction and recycling (cradle-to-grave)



M. Giani, G. Dotelli, N. Brandini, L. Zampori, Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling, Resources, Conservation and Recycling, Volume 104, Part A, 2015, pp. 224-238,https://doi.org/10.1016/j.re sconrec.2015.08.006.

Comparative life cycle assessment of asphalt pavements: scope

Functional Unit: [physical dimension and pavement performance describe the functional unit] 1 km of suburban road (4 lanes) composed of two independent roadways each with 2 lanes in each direction separated by a traffic island. The width of the pavement is 15 m and the total depth is 25 cm; lifetime was set to 15 years (which is an average lifetime according to the company experience).

To fulfill the second goal, it is extended to 30 years in order to figure out the effect of Cold In-Place Recycling of the base layer, needed to maintain the pavement after its first life.

M. Giani, G. Dotelli, N. Brandini, L. Zampori, Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling, Resources, Conservation and Recycling, Volume 104, Part A, 2015, pp. 224-238,https://doi.org/10.1016/j.re sconrec.2015.08.006.

Comparative life cycle assessment of asphalt pavements: scope

RP1

Bituminous emulsion
0.6 kg/m^2

Surface course: virgin materials and HMA
1747.5 t, 1000 m × 15 m × 0.05 m

Binder layer: virgin materials and HMA
2106 t, 1000 m × 15 m × 0.06 m

Base layer: virgin materials and HMA
4935 t, 1000 m × 15 m × 0.14 m

RP2

Bituminous emulsion
0.6 kg/m^2

Surface course: 10% RAP and HMA
1747.5 t, 1000 m × 15 m × 0.05 m

Binder layer: 20% RAP and HMA
2106 t, 1000 m × 15 m × 0.06 m

Base layer: virgin materials and HMA
4935 t, 1000 m × 15 m × 0.14 m

RP3

Bituminous emulsion
0.6 kg/m^2

Surface course: 10% RAP and HMA
1747.5 t, 1000 m × 15 m × 0.05 m

Binder layer: 20% RAP and HMA
2106 t, 1000 m × 15 m × 0.06 m

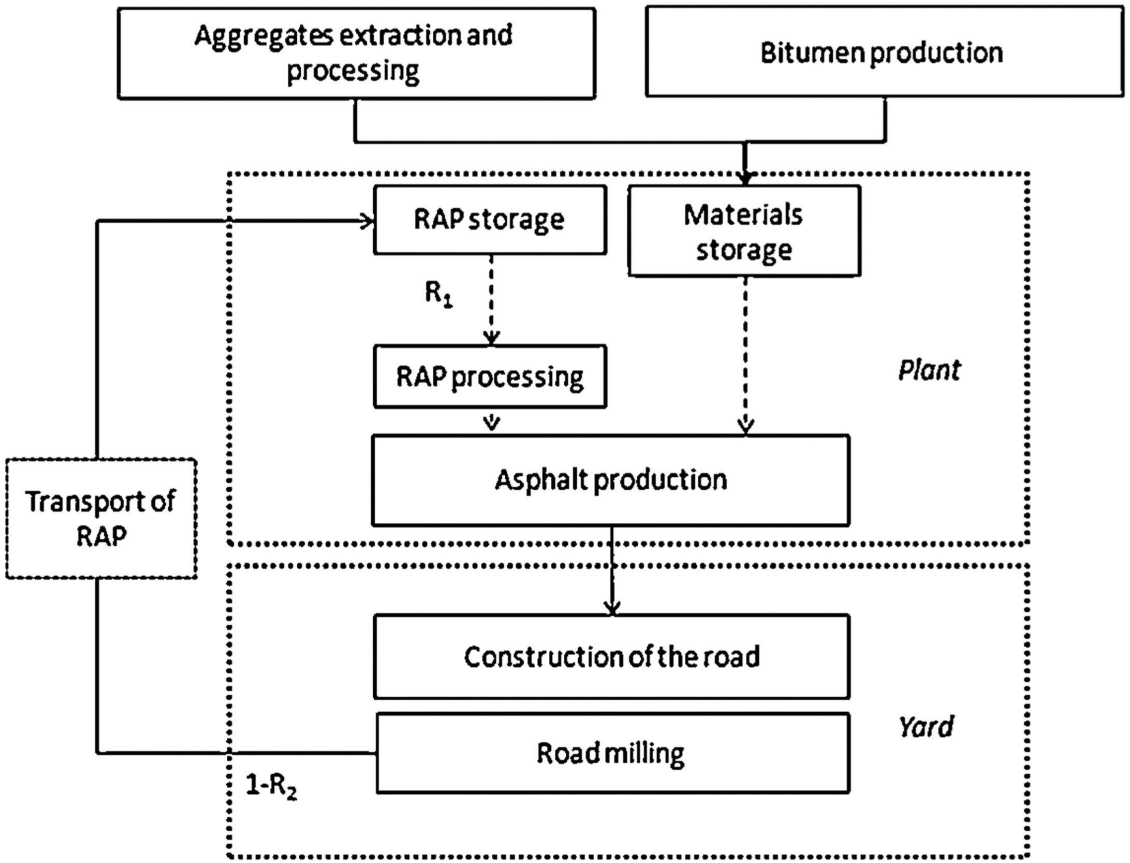
Base layer: 30% RAP and WMA
4935 t, 1000 m × 15 m × 0.14 m

Comparative life cycle assessment of asphalt pavements: scope

end-of-life

- all the materials of the pavement can be recycled and all the recycling processes and transport processes to the plant are attributed to Impresa Bacchi S.r.l.
- closed-loop recycling
- ‘cutoff’ method or “recycled content” or “100:0”: each product is assigned only the burdens directly associated with it; all benefits of recycling are given downstream to using the recycled material, with no indication of the actual rate of, or potential for, recycling.

$$\text{Emission/unit} = (1-R_1) \times E_V + (R_1 \times E_R) + (1 - R_2) \times E_D$$



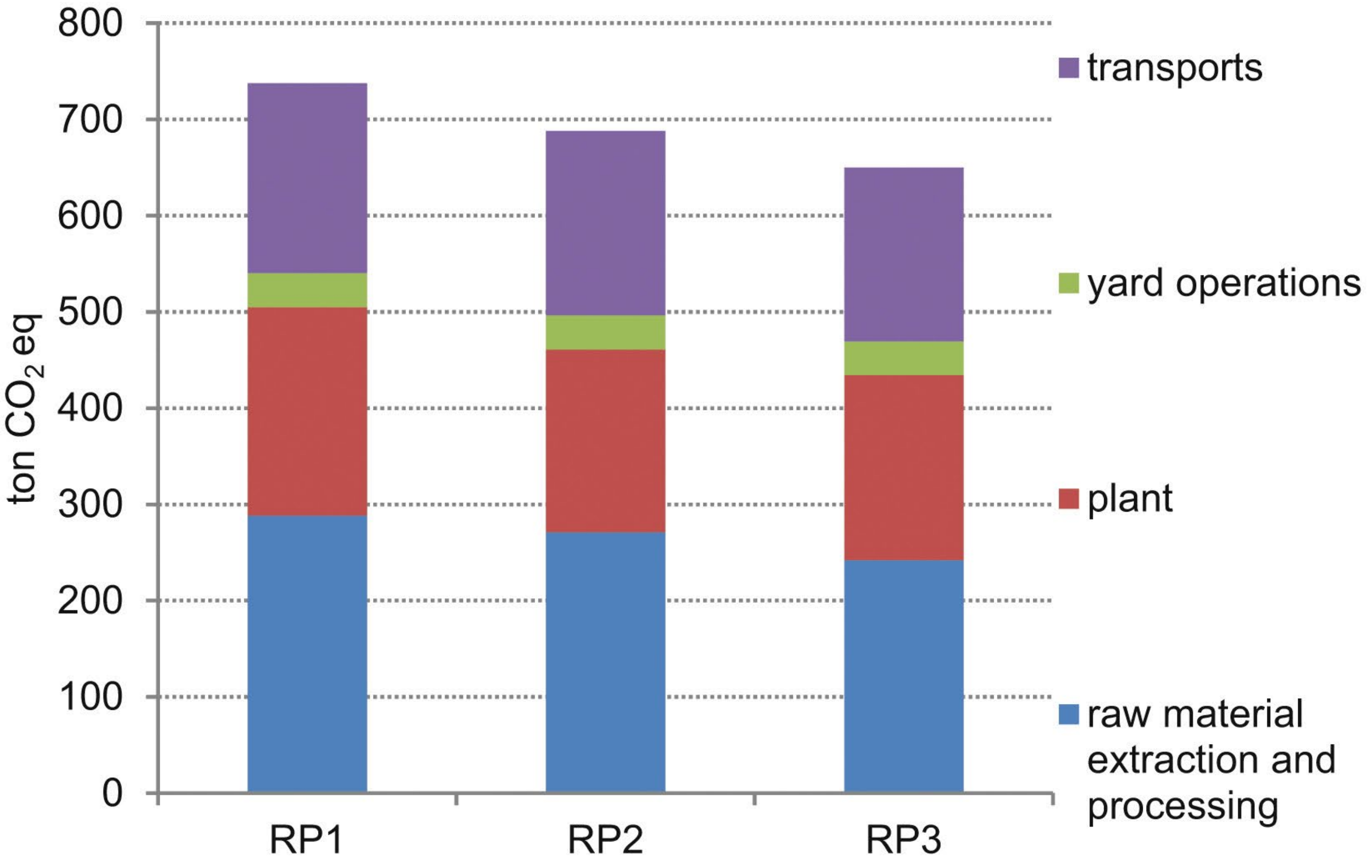
Comparative life cycle assessment of asphalt pavements: scope

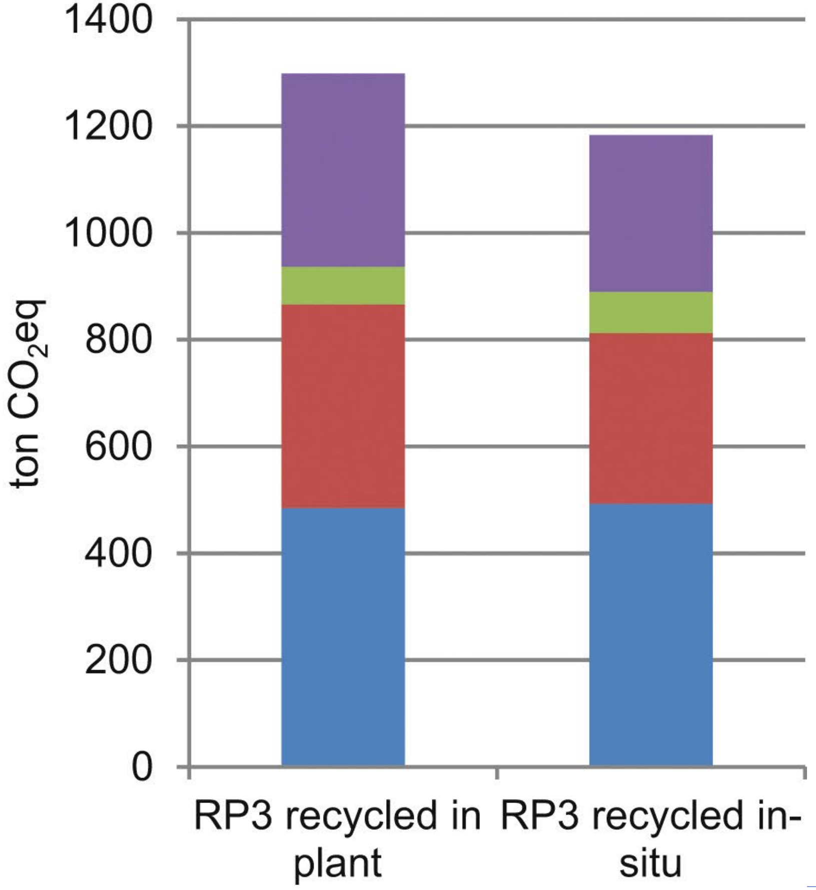
Environmental impact assessment methods

- Greenhouse Gas Protocol: climate change
- ReCiPe 2008: midpoint (H hierachist) and endpoint method
- Cumulative Energy Demand
- Water consumption (Selected LCI results) [not an impact but mass balance]

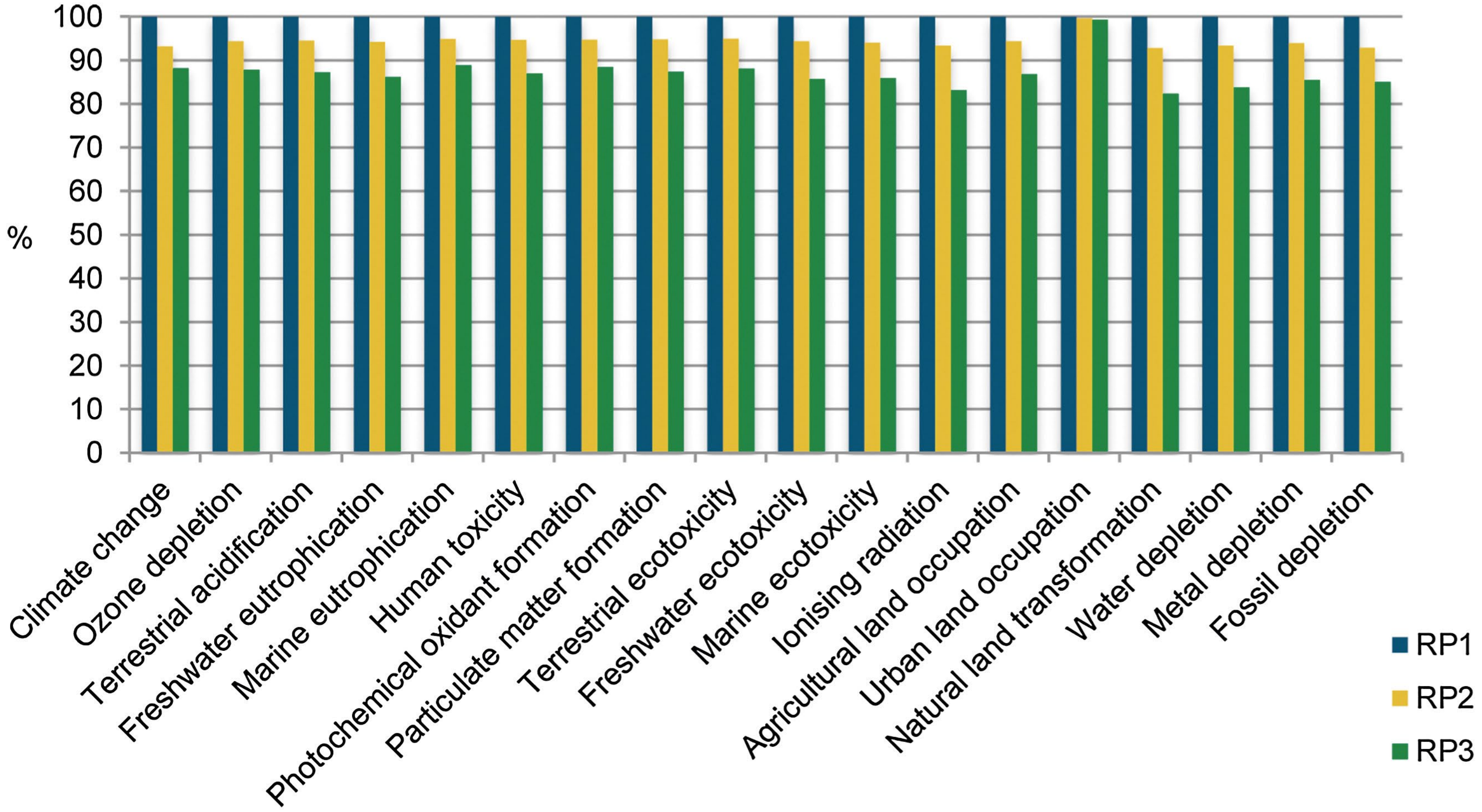
M. Giani, G. Dotelli, N. Brandini, L. Zampori, Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling, Resources, Conservation and Recycling, Volume 104, Part A, 2015, pp. 224-238,https://doi.org/10.1016/j.re sconrec.2015.08.006.

Comparative life cycle assessment of asphalt pavements: Life Cycle Impact Assessment (LCIA) - GGP



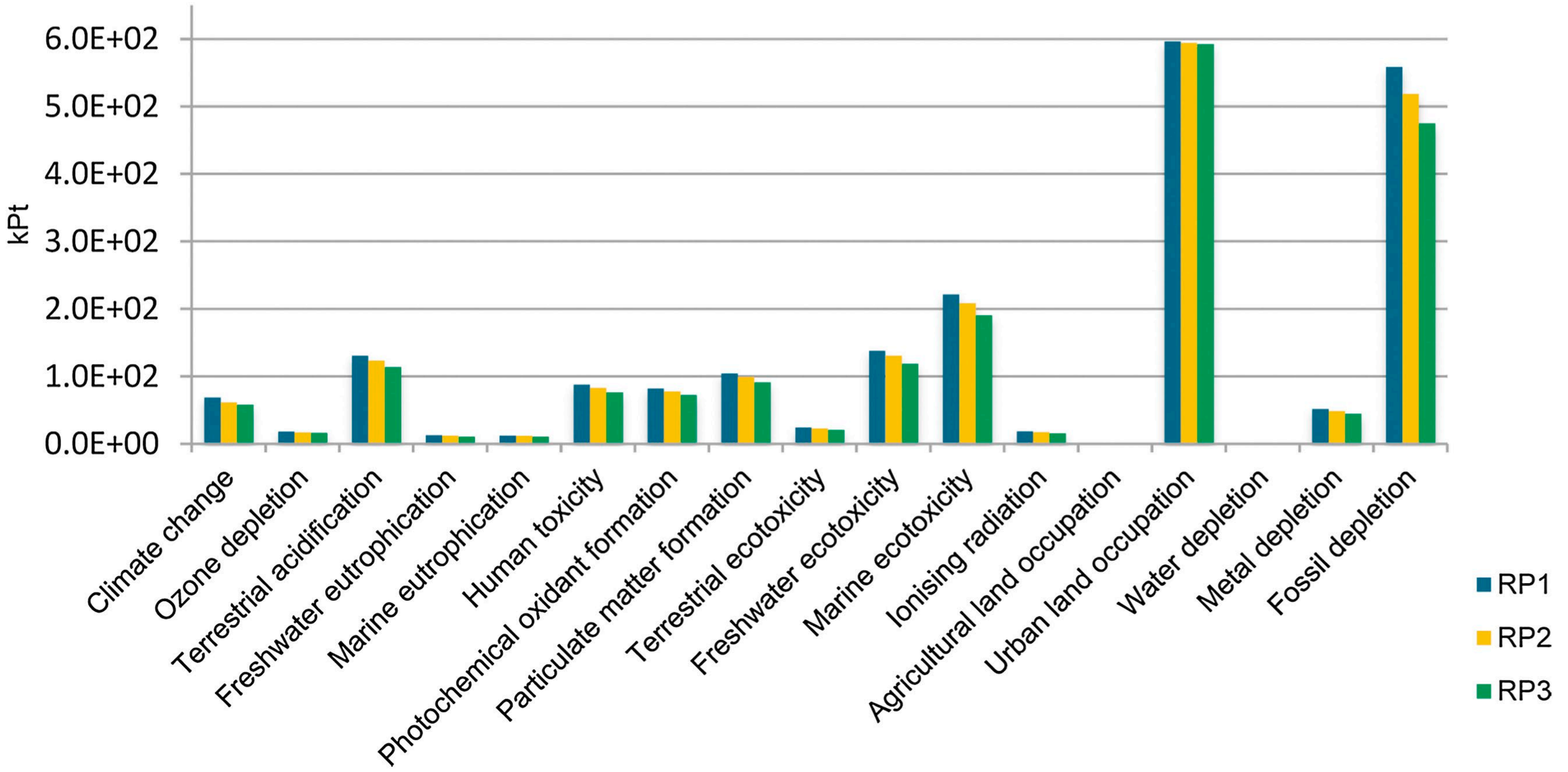


Comparative life cycle assessment of asphalt pavements: Life Cycle Impact Assessment (LCIA) – Recipe midpoint characterization

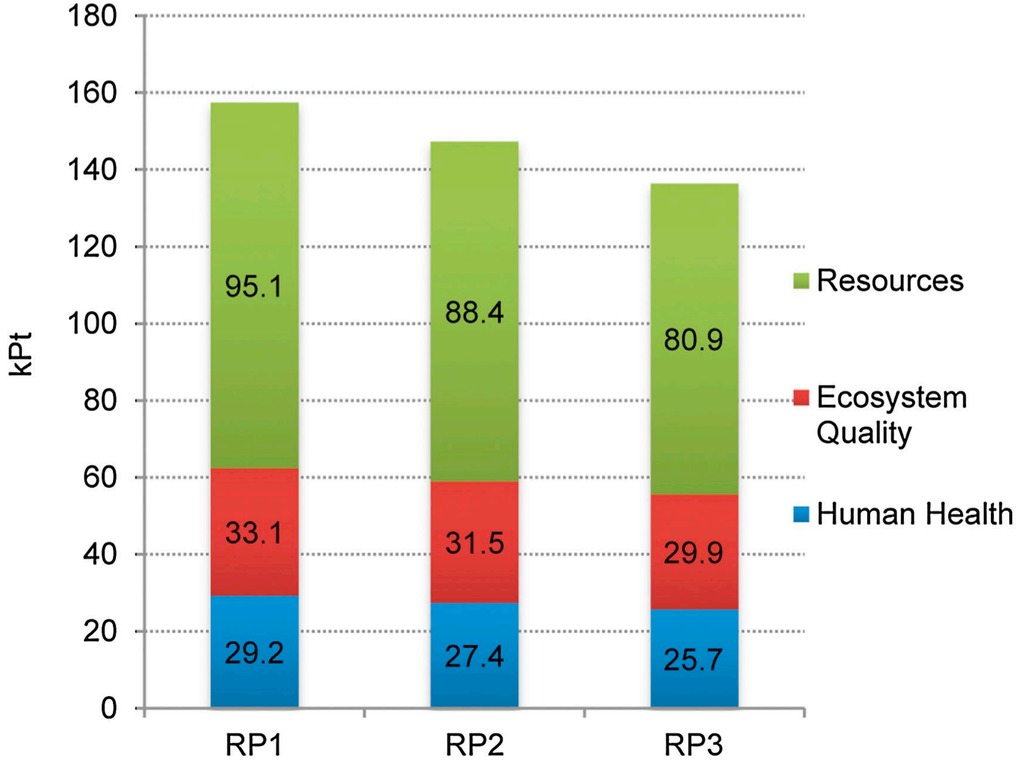


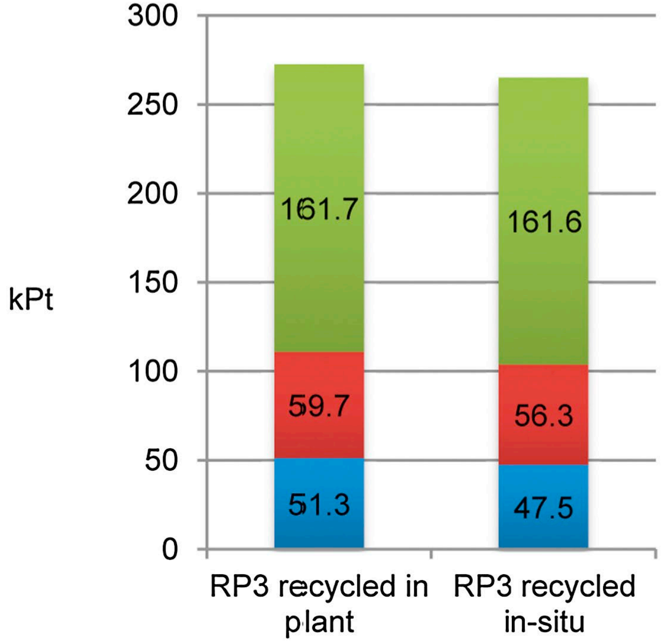
Comparative life cycle assessment of asphalt pavements: Life Cycle Impact Assessment (LCIA) – Recipe midpoint normalization

normalization factor: these factors express the annual impact score of an average European citizen for every midpoint impact category in year 2000



Comparative life cycle assessment of asphalt pavements: Life Cycle Impact Assessment (LCIA) – Recipe Endpoint - normalization & grouping & weighting





Comparative life cycle assessment of asphalt pavements: interpretation

- Extraction and production of virgin materials present the higher impacts.
- RAP combined with WMA reduce all the environmental impacts of about 10–15%.
- CIR reduces aggregate use, transport, and plant consumption but requires more bitumen.

M. Giani, G. Dotelli, N. Brandini, L. Zampori, Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling, Resources, Conservation and Recycling, Volume 104, Part A, 2015, pp. 224-238,https://doi.org/10.1016/j.re sconrec.2015.08.006.

Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: goal

- An e-road is an electrified road equipped with dynamic wireless power transfer technology (DWPT).
- The goal is the assessment of the impact of the construction and maintenance of an e-road, in order to pave the way towards a complete analysis of an electric mobility system equipped with Dynamic Wireless Power Transfer (DWPT) charging technology.
- The considered road is a motorway, where one lane has been upgraded to include DWPT equipment.
- Pilot Scale (test site in Susa)

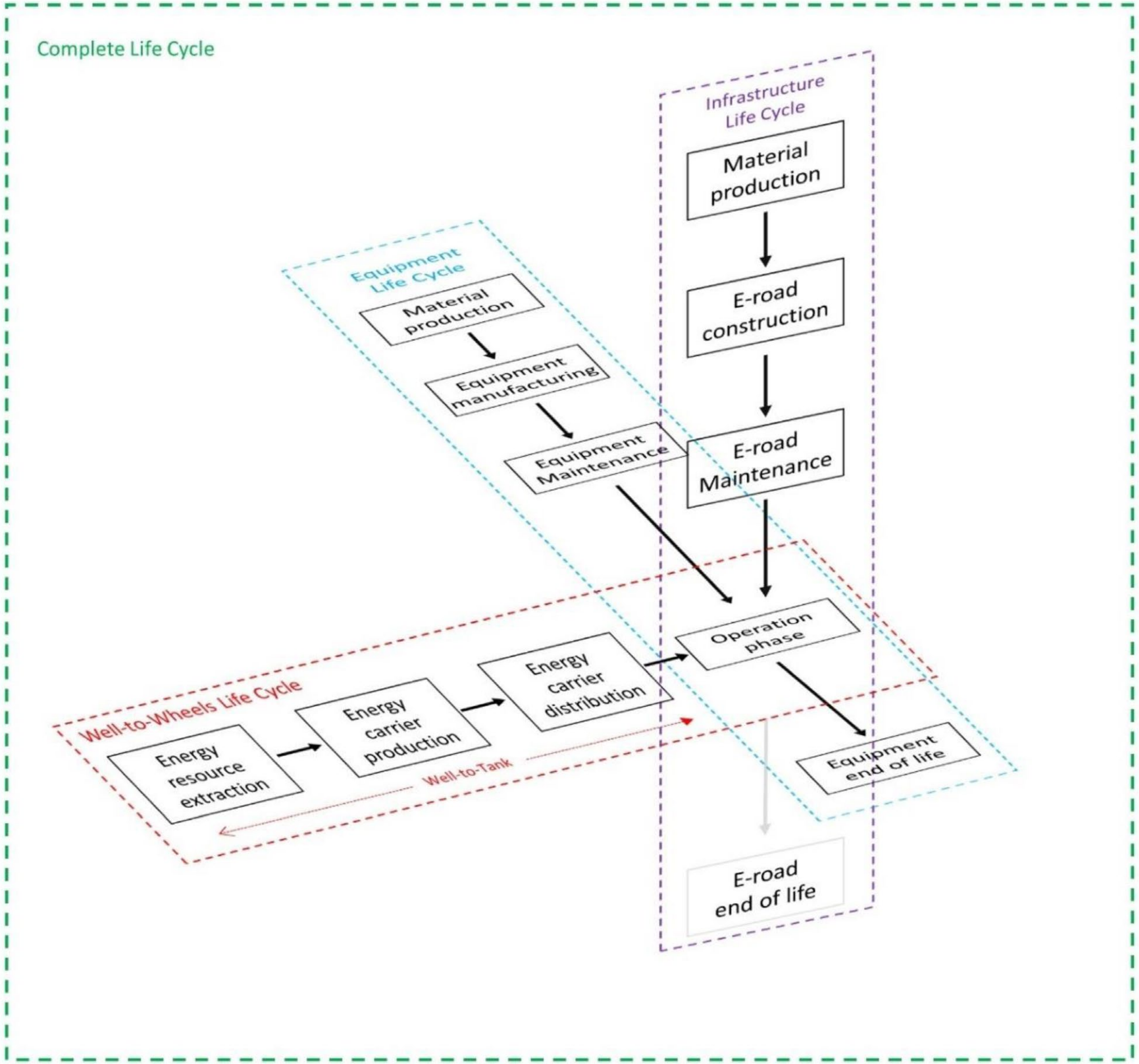
Marmiroli, B.; Dotelli, G.; Spessa, E. Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure. *Appl. Sci.* **2019**, *9*, 3117. https://doi.org/10.3390/app9153117

Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: scope

Product system: all processes that would be required to construct and maintain an e-road in Italy: material production, pavement construction, pavement maintenance, deconstruction and recycling.

Operation and End-of-Life are not included in the study.

A complete LCA to assess electric mobility would require the integration of vehicle, road infrastructure and electric energy, including charging systems.



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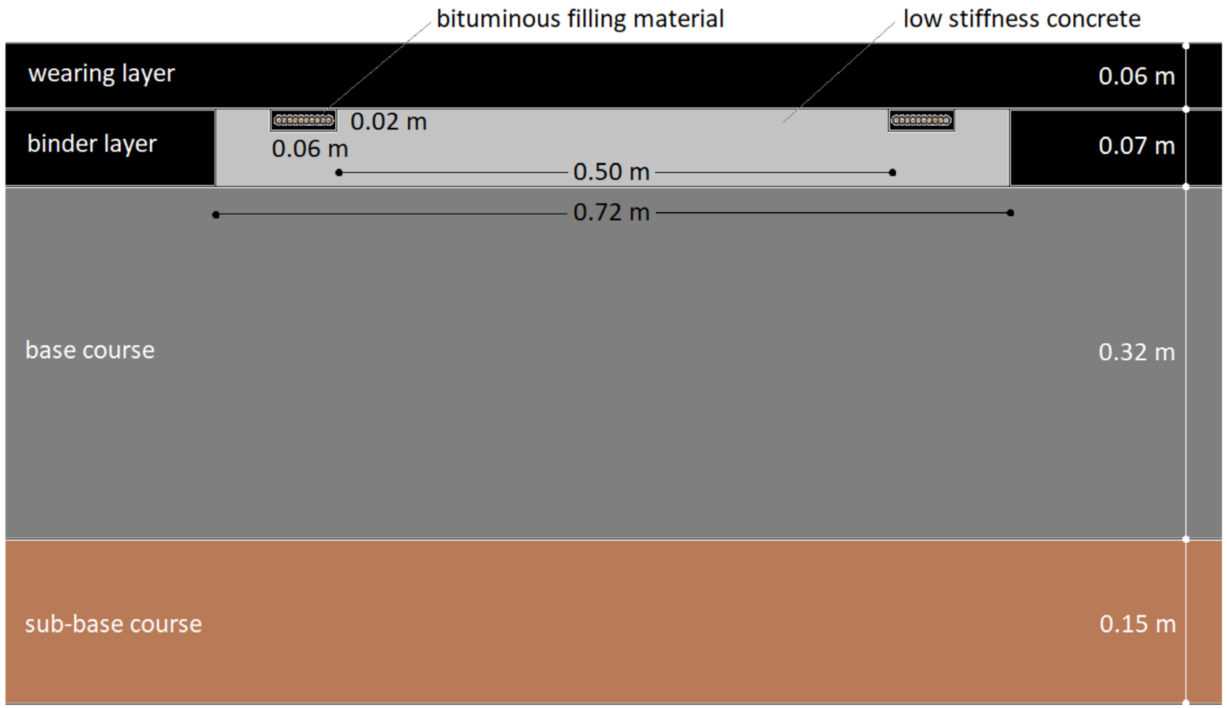
Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: scope

The functional unit is 1 km of the lane on the right of a traditional motorway—which is representative of an average European motorway—upgraded to an e-road, which is able to provide 50 kW power to vehicles and 100 kW to trucks.

The full width of the lane is 3.65 m.

The time horizon is 20 years, at the end of which the e-road could be demolished or remain in situ and serve as a support for a subsequent pavement structure.



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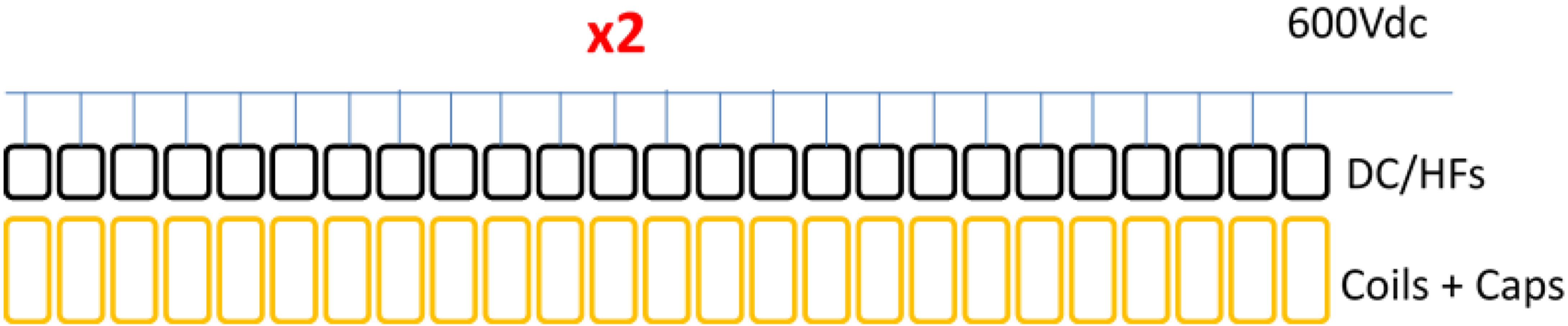
Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: scope

- The primary coils collect power from a low-voltage, three-phase, connection point and the road-side control system converts the AC voltage to DC and then to a 600 V 100 kHz rectangular waveform in order to transfer the power, through the air gap, to a secondary coil.
- The solution at the test site consists of 2 branches of 25 coils individually fed by DC/HF converters. Each coil has a DC/HF converter and the distribution is at 600 V DC. The feeder can be connected in parallel to the same cable.



Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: scope

System Boundaries: the construction phase of the e-road includes the removal of the wear and binder layers of the existing road and the application of WPT equipment as well as the following deposition and compaction of asphalt.

- Production of the raw materials;
- Transport of the raw materials to the construction site;
- Transport of the on-site equipment to the construction site;
- Equipment use (fuels);
- Construction of the e-road;
- Production of the charging (and any other electrical devices);
- Transport of the charging unit to the road construction site;
- Installation of the charging devices.

Marmiroli, B.; Dotelli, G.; Spessa, E. Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure. *Appl. Sci.* **2019**, *9*, 3117. https://doi.org/10.3390/app9153117

Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: scope

System Boundaries: maintenance phase:

- Production of the raw materials required for the maintenance;
- Transport of the raw materials to the road site;
- Transport of the on-site equipment;
- Equipment use (fuels);
- Maintenance of the charging unit and WPT components.

Marmiroli, B.; Dotelli, G.; Spessa, E. Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure. *Appl. Sci.* **2019**, *9*, 3117. https://doi.org/10.3390/app9153117

Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: impact categories

Environmental impact assessment methods

- IPCC GWP_{100} climate change
- Cumulative Energy Demand
- Abiotic depletion—Fossil Fuels (CML method)

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Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: life cycle inventory

Materials

The HMA production has been considered.

Materials	Use	Quantity Per km
Asphalt	Wear and binder layers	992,394 kg
Bituminous emulsion	Bond between layers	2190 kg
Concrete	Coil housings	113,760 kg

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Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: life cycle inventory

Materials

Wireless power transfer (WPT) components per km of e-road.

Components	Quantity Per km	Weight	Unit
Power Supply			
Main Transformer	10 units	340	kg/unit
Power metering	10 units		
Protection and shunting circuits	10 units		
AC/DC Converter	10 units	40	kg/unit
Distribution Shelter			
Shelter	10 units	10.2	kg/unit
Super-capacitors box	10 units	0.06	kg/unit
Control Power Supply	10 units	1.20	kg/unit
PE box management unit	10 units	0.00994	m^2
CSCU	10 units	0.75	kg/unit
Coil, Cabling and Capacitors			
Coil	500 coils	7.1	kg/unit
Connectors	500 units	0.009	kg/unit
Capacitors	500 units	50.5	g/unit
Power Electronics (DC/HF)			
Power Electronics board	500 units	0.00994	m^2/unit
Active Bridge	500 units		
Housing	500 units	1.0260	kg/unit
Connectors	500 units	0.009	kg/unit
Distribution lines			
Manholes	250 units	0.0162	m^3/unit
Distribution Pipes	250 m	0.161	kg/m
650VDC Distribution cables with connectors	200 m	1.04	kg/m
Signal communication cables and connectors	200 m	1.04	kg/m
Signal power supply cables and connectors	200 m	1.04	kg/m

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Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: life cycle inventory

Transports

The methodology used to calculate the consumption involves three steps:

- Calculation of the weight of the materials (aggregates, machinery, etc.) that have to be transported to the plant or to the yard;
- Definition of suitable distances from the plants to the construction sites considered representative of an average European situation;
- Definition of the type of truck used to transport each material/component.

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Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: life cycle inventory

Transports

Freight	Weight	Mileage	Vehicle Type
Asphalt	992 t	50 km	Truck 16–32 metric ton
Bituminous emulsion	2 t	50 km	Truck 16–32 metric ton
WPT components	10 t	100 km	Lorry 3.5–7.5 metric ton
Equipment	62 t	50 km	Truck 16–32 metric ton

Marmiroli, B.; Dotelli, G.; Spessa, E. Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure. *Appl. Sci.* **2019**, *9*, 3117. https://doi.org/10.3390/app9153117

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Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: life cycle inventory

Construction phase:

- Removal of the wear and binder layers, e.g., using a jack hammer and cold planer (milling machines). This can be like the normal road surface rehabilitation procedure that involves the replacement of the surface layer every few years.
- Installation of E-Road solutions: WPT components (charging unit and the associated connection pipework) delivered to the site in precast form.
- Covering with asphalt and the application of a tack coat to ensure adequate bonding between the layers.

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Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: life cycle inventory

Construction phase:

Machinery	Operation	Characteristics	Fuel Consumption
Milling machine	Removal of the wear and binder layers	Milling width 2 m; Weight 28.9 t. Two passages	111.33 kg/km
Sweeping machine	Debris removal	Weight 1.8 t, nominal power 205 kW, sweeping width 4 m average consumption 15 L/h, sweeping speed 2.5 km/h	5.01 kg/km
Paver	Wear asphalt deposition Binder asphalt deposition	operating width of 3.75 m, power 130 kW weight 19 t, 1028.8 m^2/h hourly, fuel consumption 23.2 L/h	69 kg/km 29.4 kg/km
Roller	Compacting binder Compacting wear layer	Weight 12.5 t; Roller width 2 m; Nominal Power 100 kW; Speed 0.27 km/h; Fuel consumption 21.2 L/h. Passages: 6	161 kg/km 786 kg/km
Emulsion sprayer	Spraying of a bituminous emulsion between the wear and binder layers	265 kW power, operation width 4 m operating speed 20 km/h. fuel consumption 8.3 L/h	0.346 kg/km

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Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: life cycle inventory

Maintenance phase:

The time horizon (20 years) and the frequency of the rehabilitation of the wear and binder layers in order to prevent cracking are estimated by simulation.

Based on the simulation results, wear rehabilitation is required every 25 months:

- eight wear rehabilitations during the lifetime of the e-road
- one rehabilitation is substituted by the wider "wear and binder layer rehabilitation" (at least once during the lifetime of the infrastructure, the entire asphalt layer, i.e., wear and binder, must be replaced)
- one is avoided due to the final disposal of the road at the end of its life.

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Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: life cycle inventory

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- one is avoided due to the final disposal of the road at the end of its life.

Steps included: materials production, transport to the yard, fuel consumption of machinery

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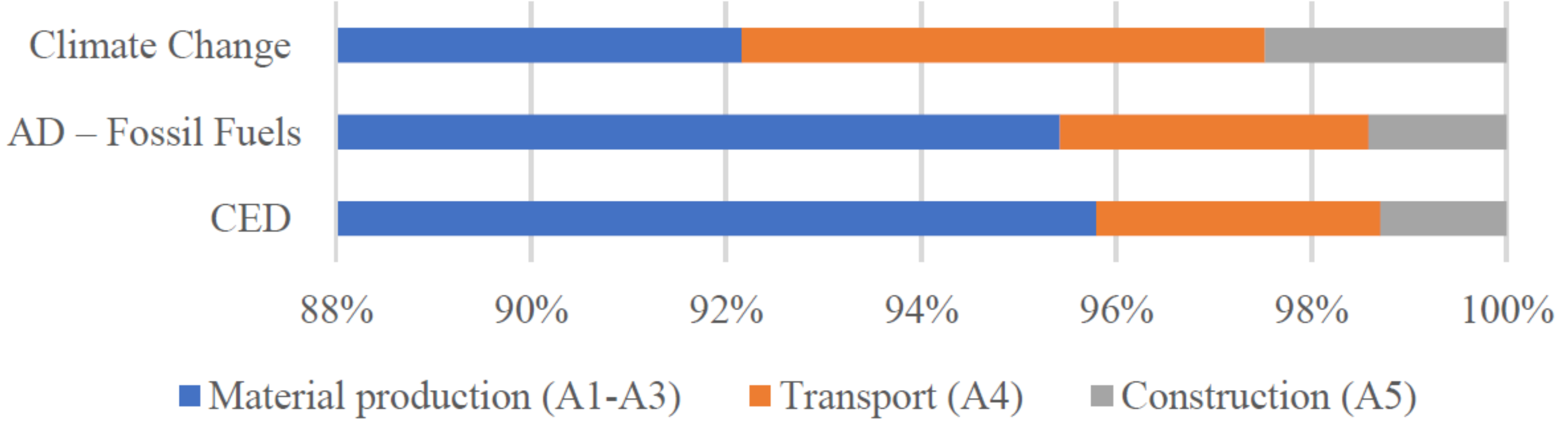
Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: life cycle impact assessment

Construction phase:

Phase	CED [MJ/km]	AD—Fossil Fuels [MJ/km]	Climate Change [kg CO_2-eq/km]
Material production	4,752,868	4,313,584	155,114
Transport	144,597	143,051	9040
Construction	64,227	63,941	4162



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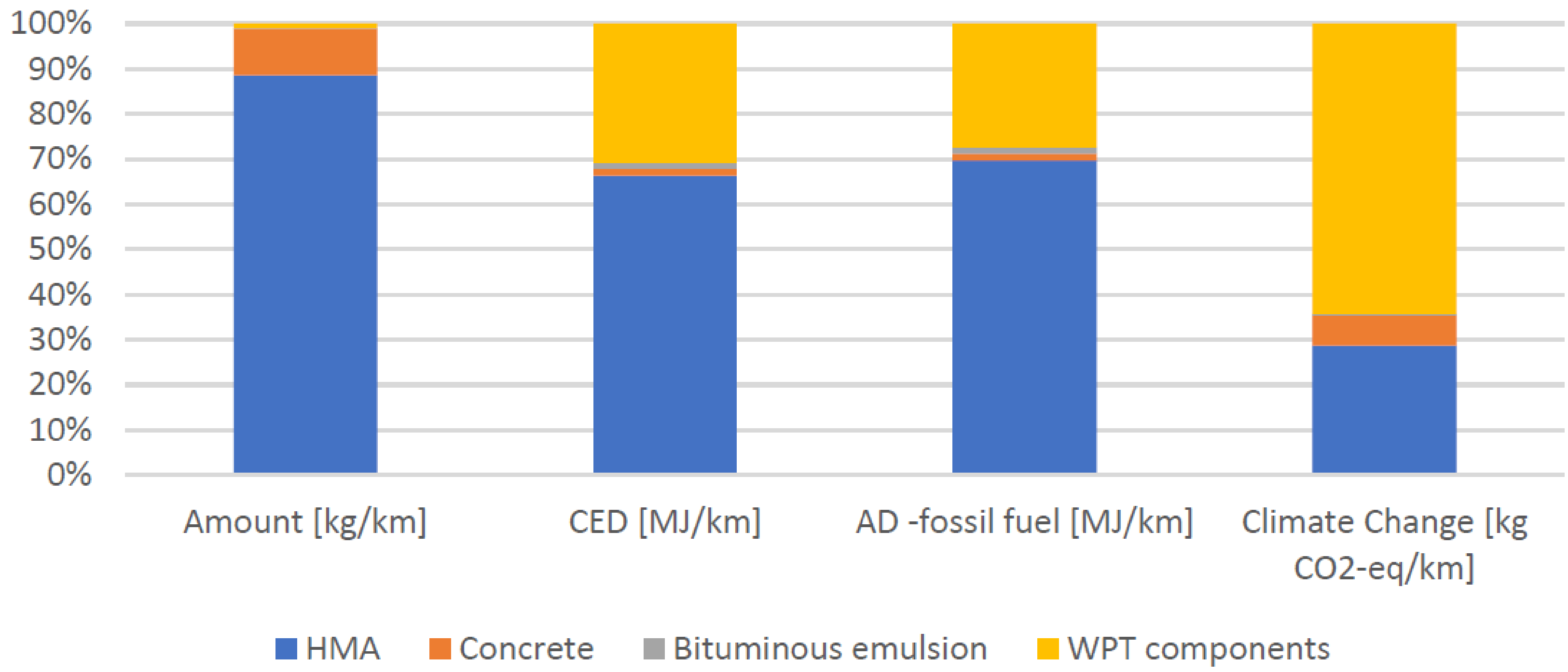
Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: life cycle impact assessment

Construction phase: materials



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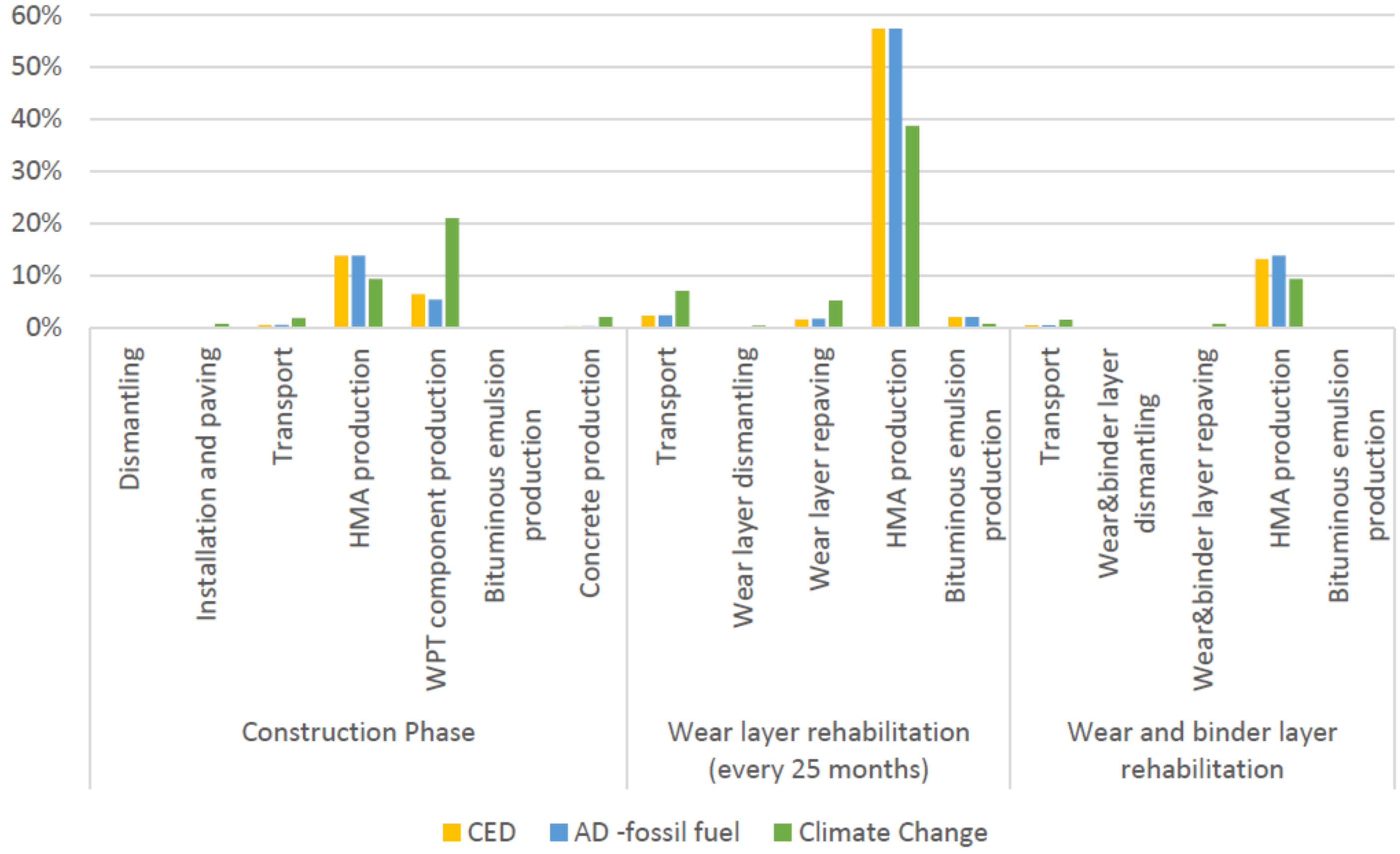
Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: life cycle impact assessment

Construction and maintenance



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Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure: life cycle interpretation

- The predominance of the WPT component production in the construction phase, more than 30% of the share in all the impact categories, even though they are less than 1% of the total components in weight.
- Maintenance is the phase with the highest impact due to the structural features of the e-road.
- There is high uncertainty about both the durability of pavements and WPT components in e-roads.

Marmiroli, B.; Dotelli, G.; Spessa, E. Life Cycle Assessment of an On-Road Dynamic Charging Infrastructure. *Appl. Sci.* **2019**, *9*, 3117. https://doi.org/10.3390/app9153117

Life-Cycle Assessment of a Fiber-Reinforced Polymer-Reinforced Concrete Bridge in Florida

The selected case study is an FRP-RC/PC short-spanned vehicular bridge named the Halls River Bridge (HRB).

The structure is located in Homosassa, FL.

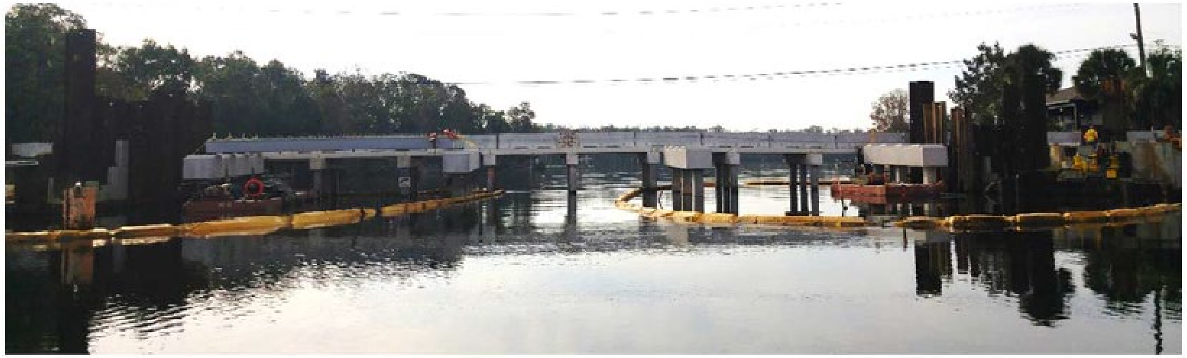
The performance of the structure is compared with that of a traditional CS-RC/PC alternative.

T. Cadenazzi, G. Dotelli, M. Rossini, S. Nolan, and A. Nanni, "Life-Cycle Cost and Life-Cycle Assessment Analysis at the Design Stage of a Fiber-Reinforced Polymer-Reinforced Concrete Bridge in Florida," Advances in Civil Engineering Materials 8, no. 2 (2019): 128–151. https:// doi.org/10.1520/ACEM20180113

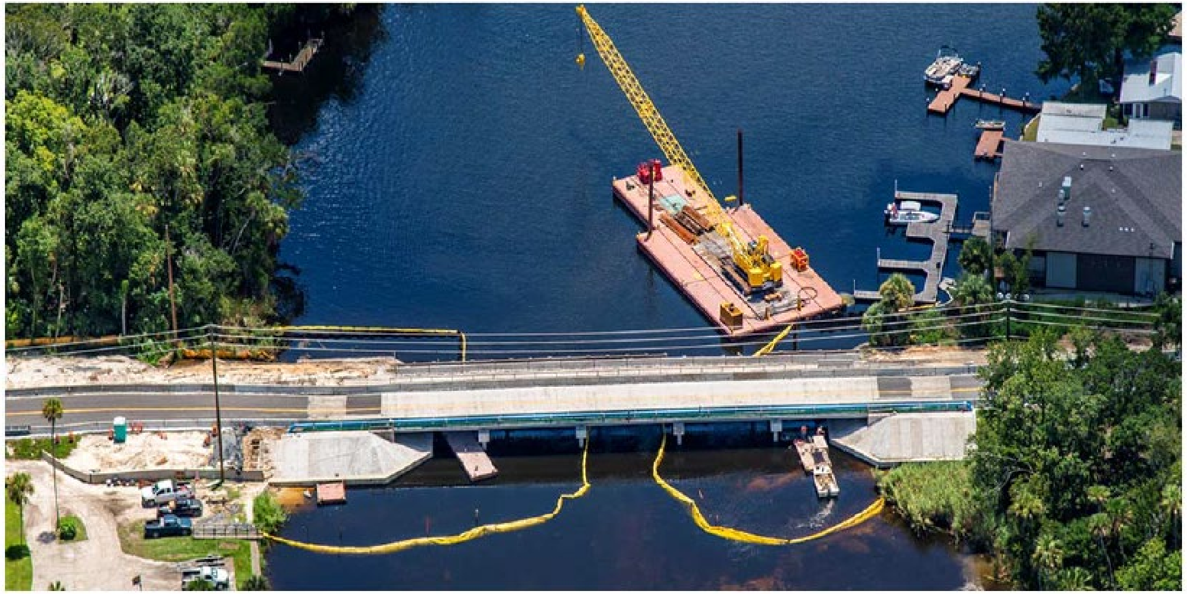
Life-Cycle Assessment of a Fiber-Reinforced Polymer-Reinforced Concrete Bridge in Florida

(A) HRB substructure

(B) north side after completion.



(A)



(B)

T. Cadenazzi, G. Dotelli, M. Rossini, S. Nolan, and A. Nanni, "Life-Cycle Cost and Life-Cycle Assessment Analysis at the Design Stage of a Fiber-Reinforced Polymer-Reinforced Concrete Bridge in Florida," Advances in Civil Engineering Materials 8, no. 2 (2019): 128–151. https:// doi.org/10.1520/ACEM20180113

Life-Cycle Assessment of a Fiber-Reinforced Polymer-Reinforced Concrete Bridge in Florida: goal

The main goal is to support and promote the deployment of innovative technologies in infrastructure.

The LCA of the HRB is performed to assess the level of environmental sustainability of a transportation infrastructure built only with noncorrosive FRP reinforcement.

To highlight possible benefits associated with the deployment of FRP reinforcement, the environmental performance of the FRP-RC/PC design is compared with a traditional CS-RC/PC alternative.

Glass Fiber-Reinforced Polymer (GFRP) bars and Carbon Fiber-Reinforced Polymer (CFRP) strands are validated corrosion-resistant solutions for Reinforced Concrete (RC) and Prestressed Concrete (PC) structures.

Studies on the performance of Fiber-Reinforced Polymer (FRP) reinforcement in seawater and salt-contaminated concrete have been conducted and show that the technology is a viable solution.

The economic and environmental implications of FRP-RC/PC deployment have not been fully investigated.

T. Cadenazzi, G. Dotelli, M. Rossini, S. Nolan, and A. Nanni, "Life-Cycle Cost and Life-Cycle Assessment Analysis at the Design Stage of a Fiber-Reinforced Polymer-Reinforced Concrete Bridge in Florida," Advances in Civil Engineering Materials 8, no. 2 (2019): 128–151. https:// doi.org/10.1520/ACEM20180113

Life-Cycle Assessment of a Fiber-Reinforced Polymer-Reinforced Concrete Bridge in Florida: scope

System product:

- the Homosassa Halls River Bridge (HRB) with a service life of 75 years for the CS-RC/PC alternative and a service life of 100 years for the FRP-RC/PC solution for comparison.
- The study is performed at the design stage.
- The scenario is from cradle to grave.
- Different service life scenarios, and thus different EOL scenarios, change the analysis substantially.
- For the purpose of comparing the 2 alternatives for which a service life of 100 years is requested, the analysis of the CS-RC/PC bridge alternative takes into account one demolition and one reconstruction.

T. Cadenazzi, G. Dotelli, M. Rossini, S. Nolan, and A. Nanni, "Life-Cycle Cost and Life-Cycle Assessment Analysis at the Design Stage of a Fiber-Reinforced Polymer-Reinforced Concrete Bridge in Florida," Advances in Civil Engineering Materials 8, no. 2 (2019): 128–151. https:// doi.org/10.1520/ACEM20180113

Life-Cycle Assessment of a Fiber-Reinforced Polymer-Reinforced Concrete Bridge in Florida: scope

For the purpose of the analysis (i.e., to evaluate the environmental performance of an infrastructure reinforced with only FRP), the FRP-RC/PC bridge alternative is chosen as the Functional Unit (FU) considering its entire service life of 100 years.

An alternative CS-RC/PC design is considered for comparison.

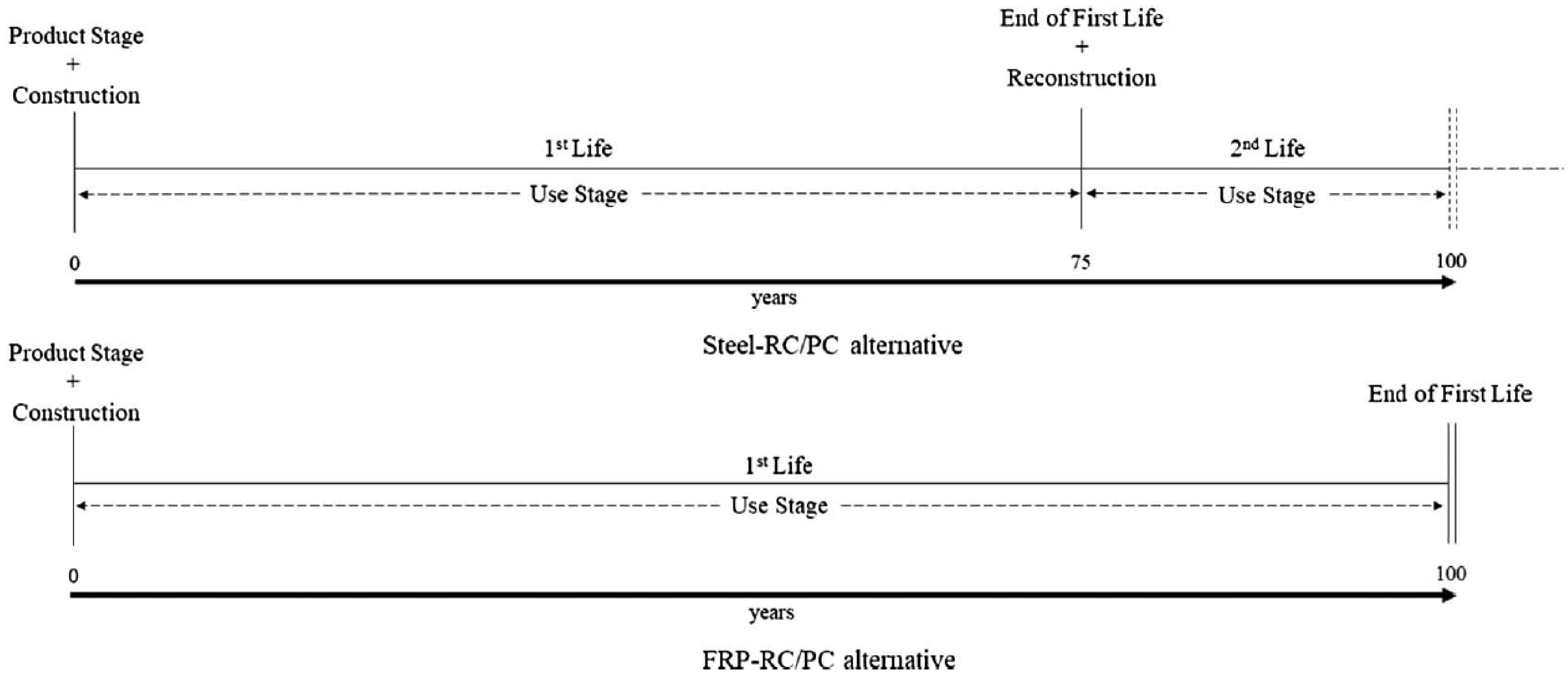
For consistency, it is necessary to also adopt the same FU for the CS-RC/PC alternative considering a reference period of 100 years.

The service life of the CS-RC/PC alternative is limited to 75 years. Thus, it is assumed that after 75 years, the bridge is demolished and a new one is rebuilt with the same technology.

T. Cadenazzi, G. Dotelli, M. Rossini, S. Nolan, and A. Nanni, "Life-Cycle Cost and Life-Cycle Assessment Analysis at the Design Stage of a Fiber-Reinforced Polymer-Reinforced Concrete Bridge in Florida," Advances in Civil Engineering Materials 8, no. 2 (2019): 128–151. https:// doi.org/10.1520/ACEM20180113

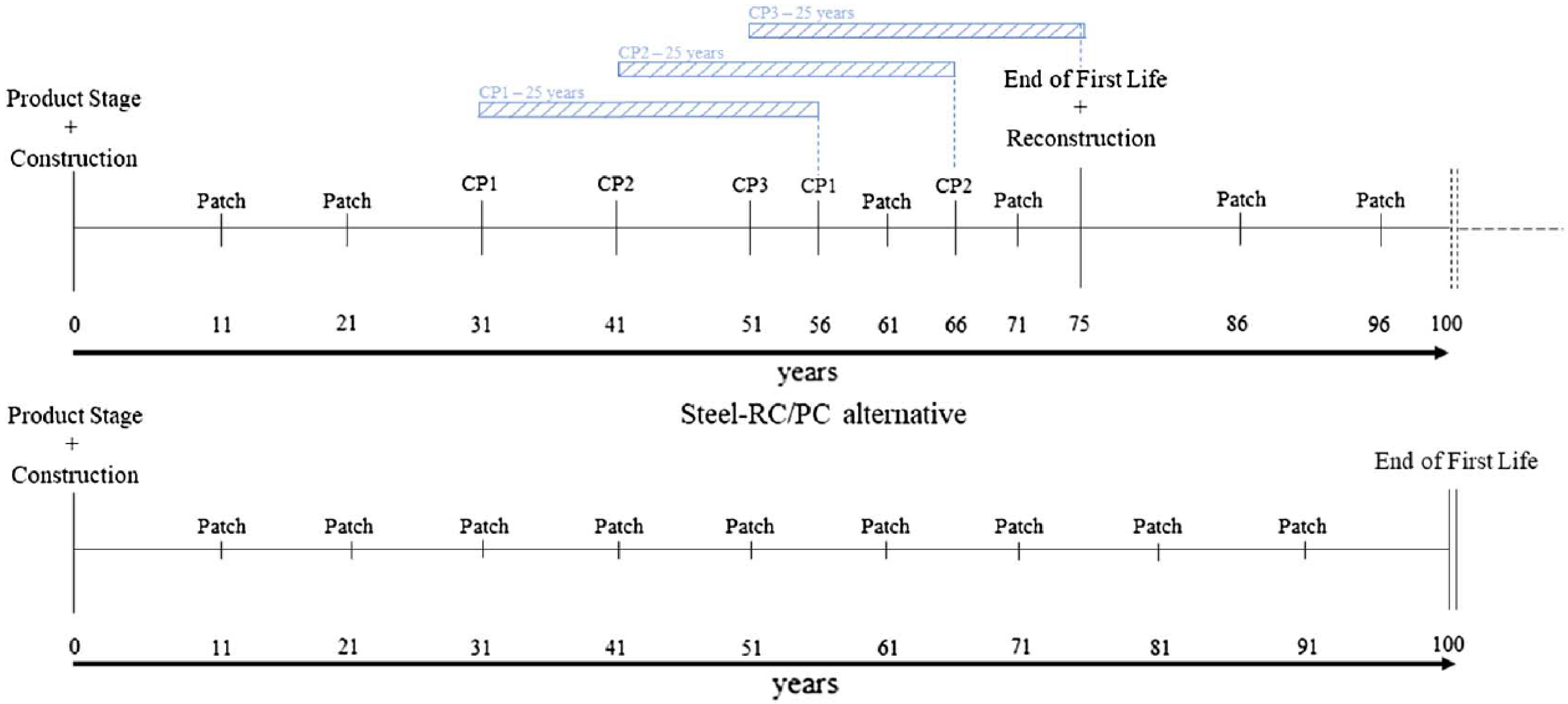
Life-Cycle Assessment of a Fiber-Reinforced Polymer-Reinforced Concrete Bridge in Florida: scope

System boundaries



Life-Cycle Assessment of a Fiber-Reinforced Polymer-Reinforced Concrete Bridge in Florida: scope

System boundaries: maintenance details



Life-Cycle Assessment of a Fiber-Reinforced Polymer-Reinforced Concrete Bridge in Florida: life cycle impact assessment

Impact assessment method: TRACI (US)

FRP-RC/PC environmental impacts

Item	Product Stage [A1–A3]	Transport to Job Site [A4]	Construction [A5]	Use	EOL	Total
Ozone depletion, kg CFC-11 eq	0.486	0.0197	0.0182	0.000359	0.0102	0.534
Global warming, kg CO_2 eq	883,000	81,200	83,900	8,690	34,300	1,090,000
Photochemical oxidant creation, kg O_3 eq	51,000	9,430	6,400	422	4,390	71,700
Acidification, kg SO_2 eq	4,460	421	291	32	185	5,390
Eutrophication, kg N eq	1,460	92	150	13	42	1,760

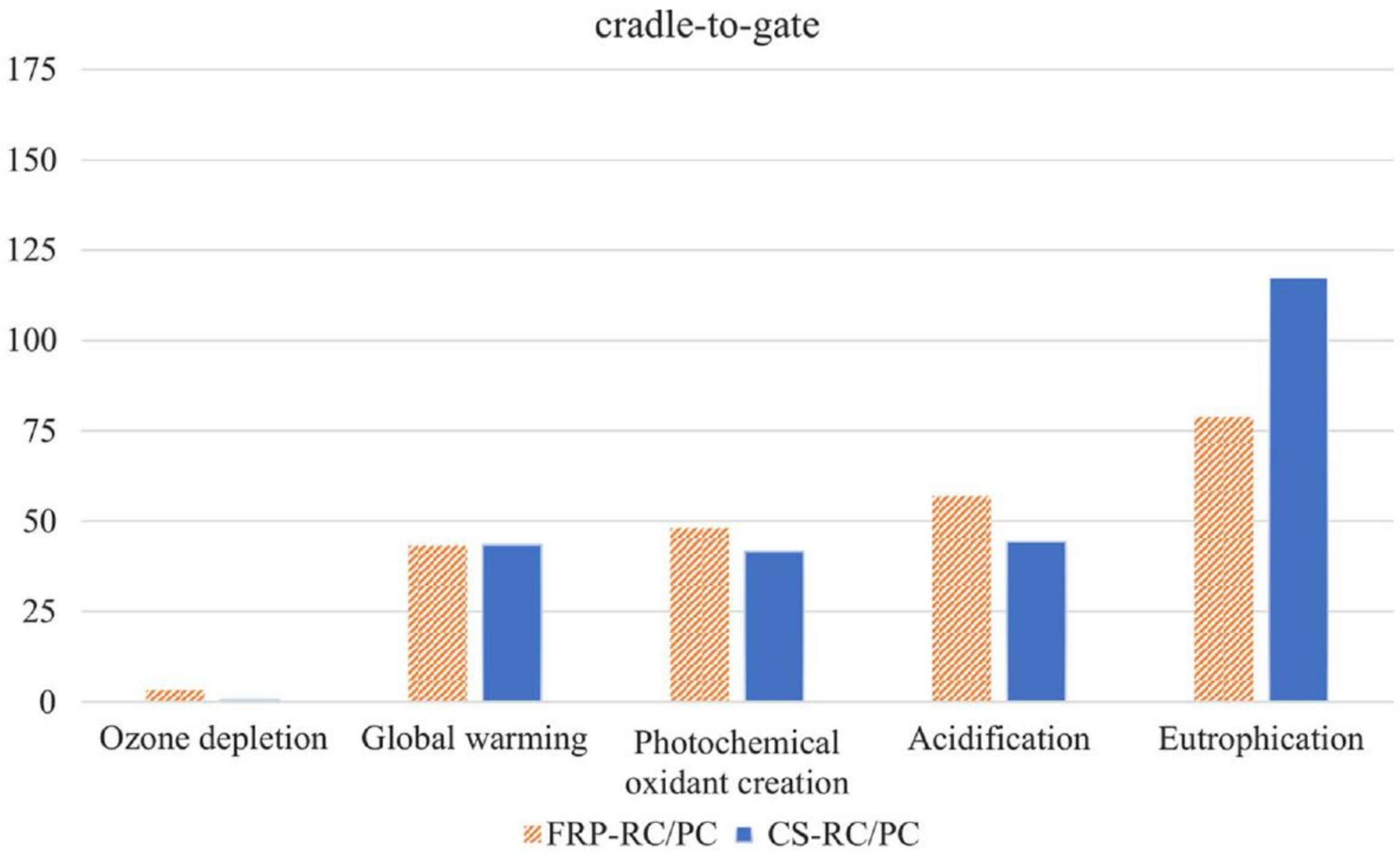
Life-Cycle Assessment of a Fiber-Reinforced Polymer-Reinforced Concrete Bridge in Florida: life cycle impact assessment

Impact assessment method: TRACI (US)

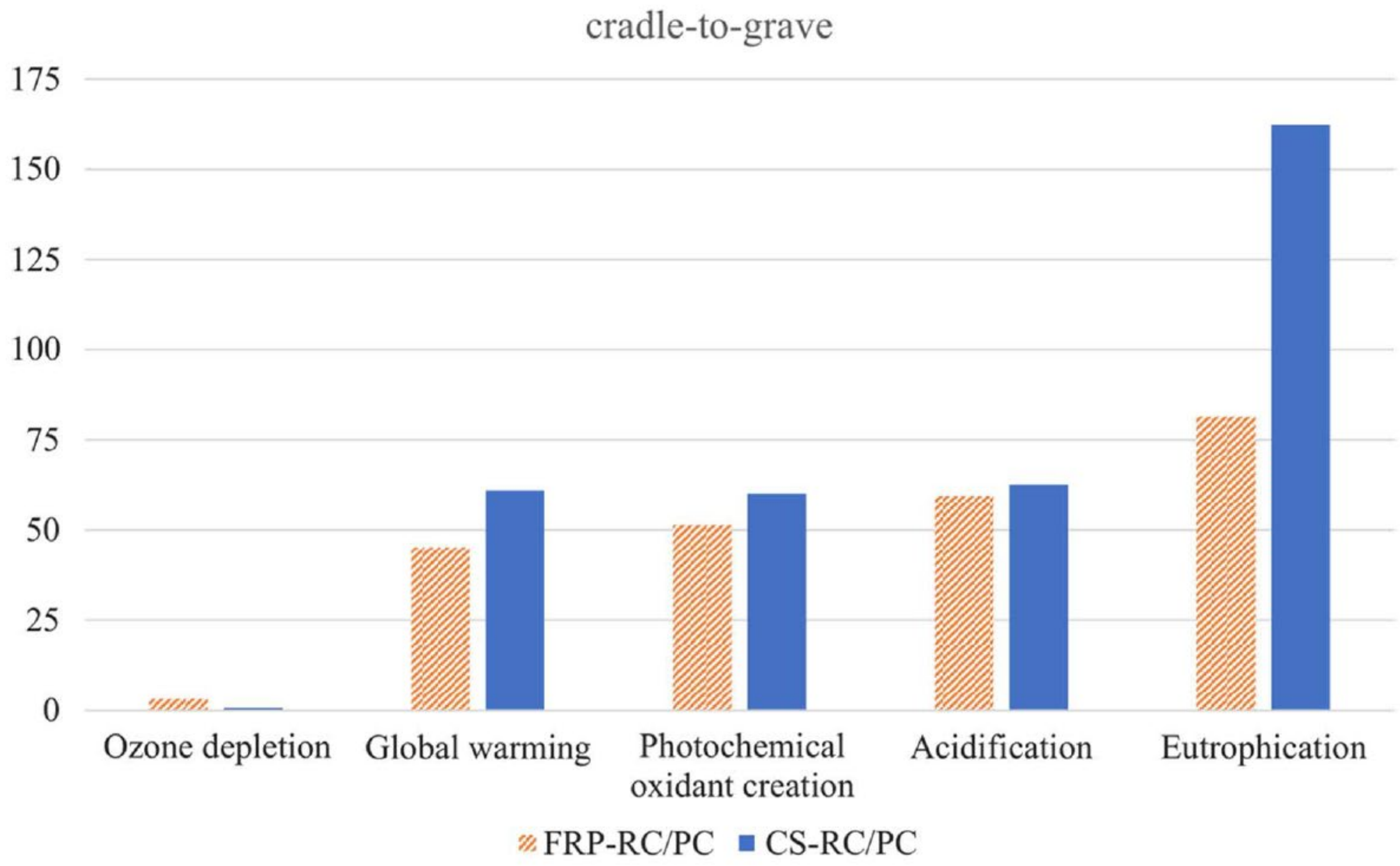
CS-RC/PC environmental impacts

Item	Product Stage [A1–A3]	Transport to Job Site [A4]	Construction [A5]	Use	EOL	Total
Ozone depletion, kg CFC-11 eq	0.0619	0.0265	0.0242	0.00175	0.011	0.125
Global warming, kg CO_2 eq	1,180,000	109,000	112,000	35,200	36,700	1,480,000
Photochemical oxidant creation, kg O_3 eq	57,000	11,800	8,530	1,530	4,740	83,500
Acidification, kg SO_2 eq	4,480	495	388	121	199	5,680
Eutrophication, kg N eq	3,070	120	200	77	45	3,510

Life-Cycle Assessment of a Fiber-Reinforced Polymer-Reinforced Concrete Bridge in Florida: life cycle impact assessment



Life-Cycle Assessment of a Fiber-Reinforced Polymer-Reinforced Concrete Bridge in Florida: life cycle impact assessment



The End

Thanks for the attention – ready for questions