CIVIL-239
Engineering a sustainable built environment

Lecture 08

Embodied carbon of materials and structures

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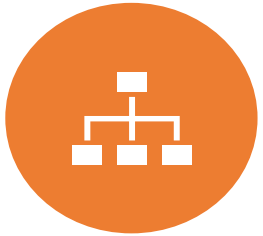
Hes·so GENÈVE
Haute Ecole Spécialisée de Suisse occidentale

h e p i a
Haute école du paysage, d'ingénierie et d'architecture de Genève

November 12th 2025

session overview

BASICS OF STRUCTURAL DESIGN

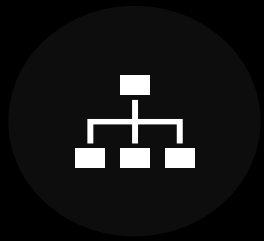


IMPACTS OF STRUCTURES

MATERIALS

STRUCTURAL SYSTEMS

LIFESPAN



BASICS OF STRUCTURAL DESIGN

what is a structure?

Join at
slido.com
#2474112

what is a structure?

- system of elements in a construction with a load-bearing role
- it transfers the loads applied to the construction to its supports
- unique, linked to its location and environment

transport infrastructures

Chillon viaduct
highway bridge

Landwasser viaduct
railway bridge

Route de la Pierre, Ecublens
footbridge

Gotthard railway tunnel

building structures

Halle Bleue, Blue Factory, Fribourg
steel frame

Bâtiment B, Blue Factory, Fribourg
wood frames

Favarol Papaux factory, Treyvaux
Reinforced concrete structure

energy infrastructures

Grande Dixence Dam

Electricity pylon
Swissgrid

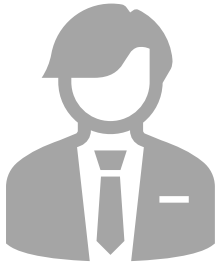
Leibstadt Nuclear Power Plant

geotechnical structures

Liaison Ouest, Plateforme 10, Lausanne
retaining wall

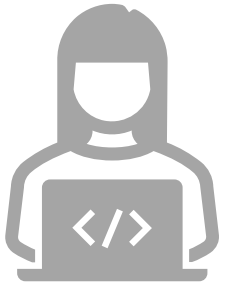
Elysée/mudac, Plateforme 10, Lausanne
excavation supports

roles



Owner

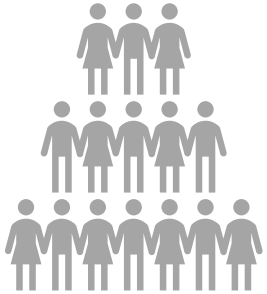
(maître d’ouvrage)



Designer and planner
(architects and engineers)

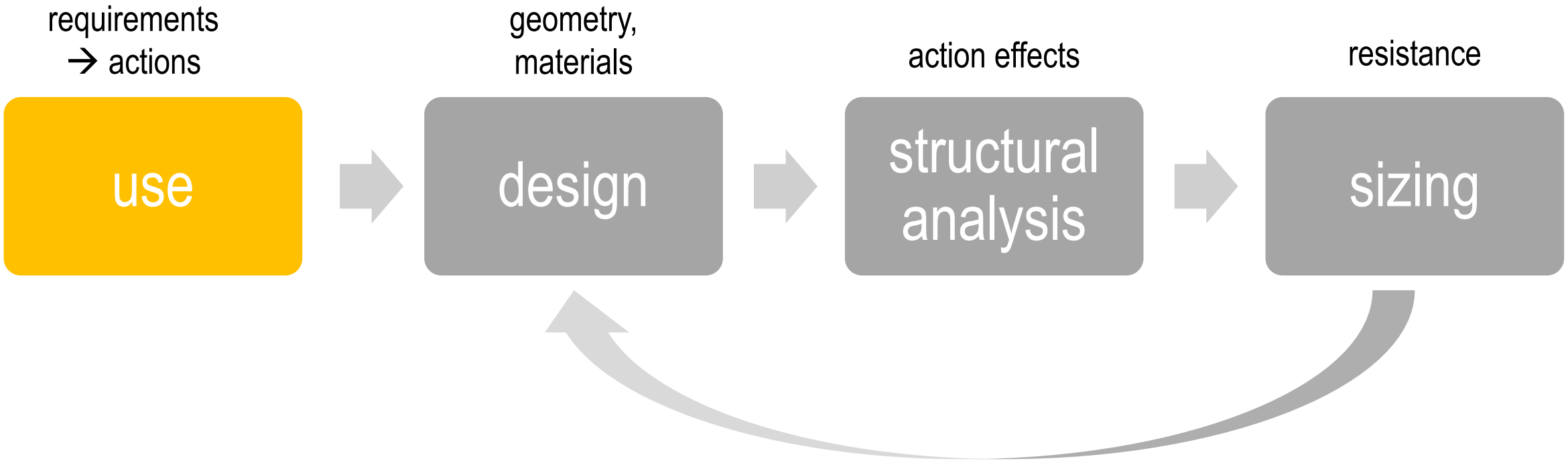
Builders

(contractors)

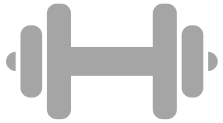


Users

design process



actions



Self-weight

of the structure and other added layers

Use loads

Buildings:

- Housing: 2 kN/m^2
- Office: 3 kN/m^2
- Commercial: 5 kN/m^2

Traffic (road, railway, non-motorized)

Soil

Earth pressure

Climate

wind, snow, temperature

Accidents

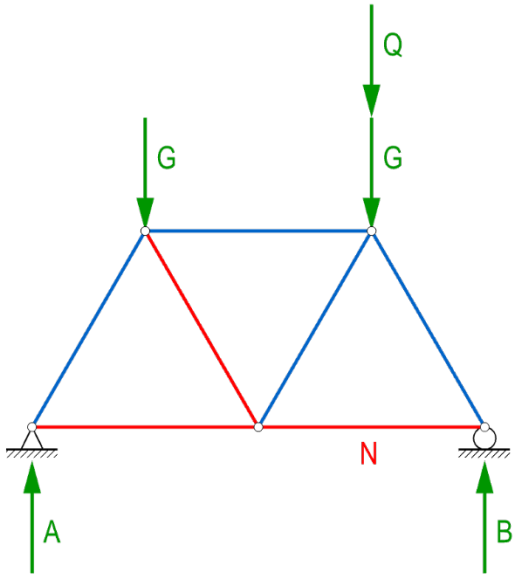
chocs, fire, earthquake

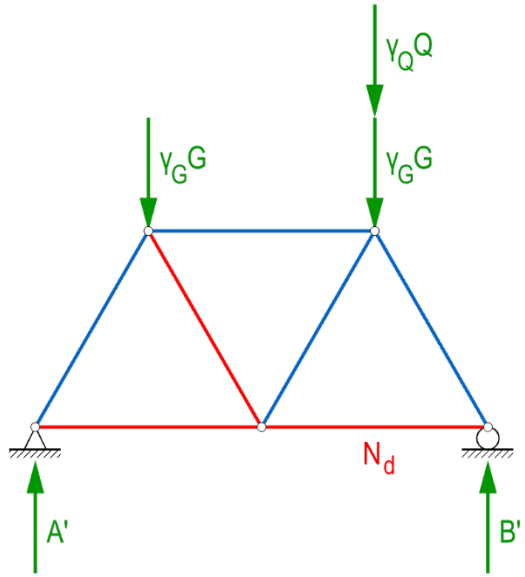
design values – actions

› **design loads (actions) are combined:** $\boxed{E_d = \gamma_G G + \gamma_Q Q}$

› **Load factors γ_G et γ_Q** amplify the self-weight loads G and variable loads Q

› **Action effect E_d** obtained for given load combination

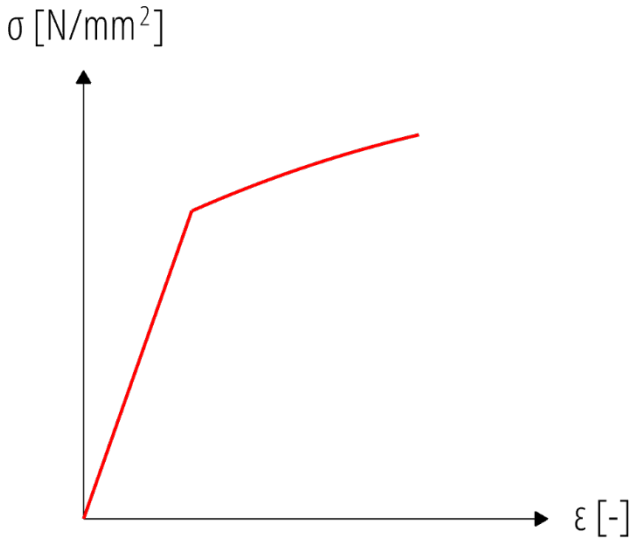




design values – materials

› **Material design strength f_d :** $$f_d = \frac{f}{\gamma_M}$$

› **Resistance factors γ_M** that consider material imperfections (natural or manufacturing)



Steel	γ_M = 1.05
Steel rebars	γ_M = 1.15
Concrete	γ_M = 1.5
Timber	γ_M = 1.5-1.7

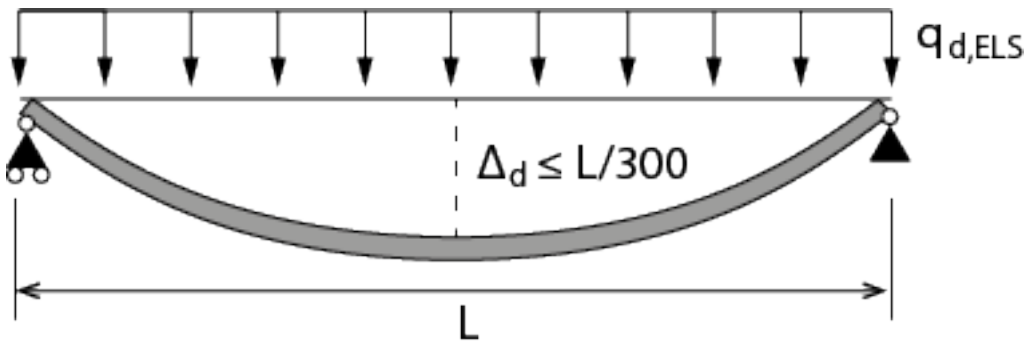
limit states

Serviceability Limit State (SLS)

› Verify that the structure will allow a normal **use**

Deformations due to action ≤ Allowable deformations

Example: Verification of deflections ≤Δ

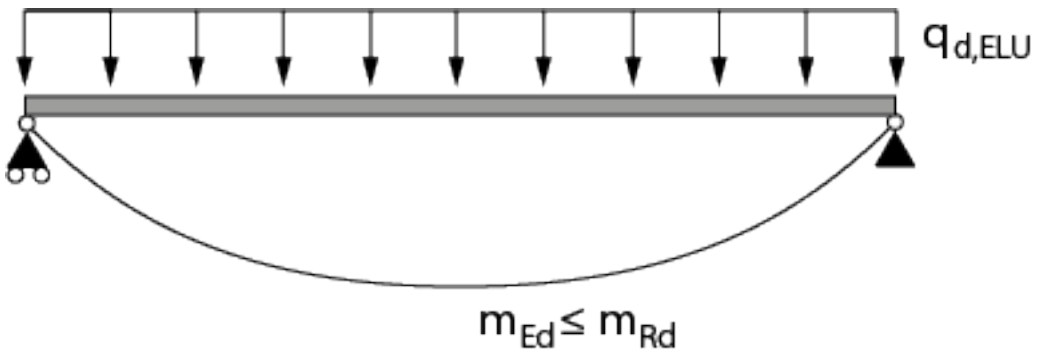


Ultimate Limit State (ULS)

› Verify structural safety and stability
→ avoid **failure**

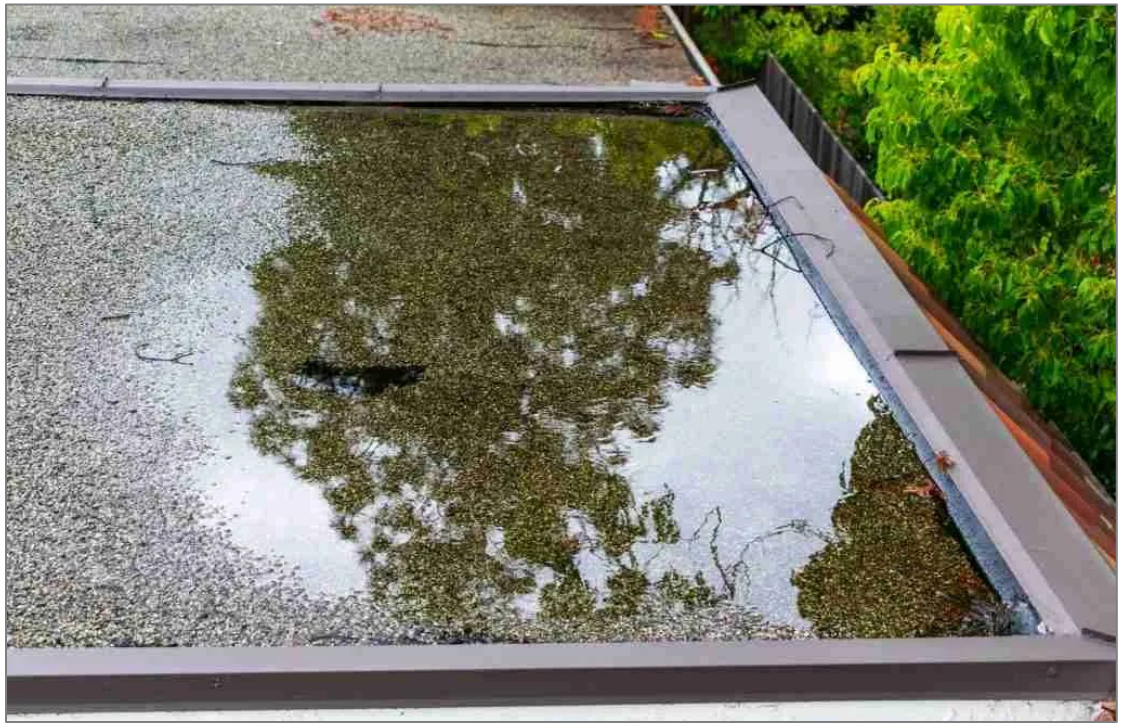
Action effects ≤ Structural resistance

Example: Verification of bending resistance



deformations leading to dysfunction

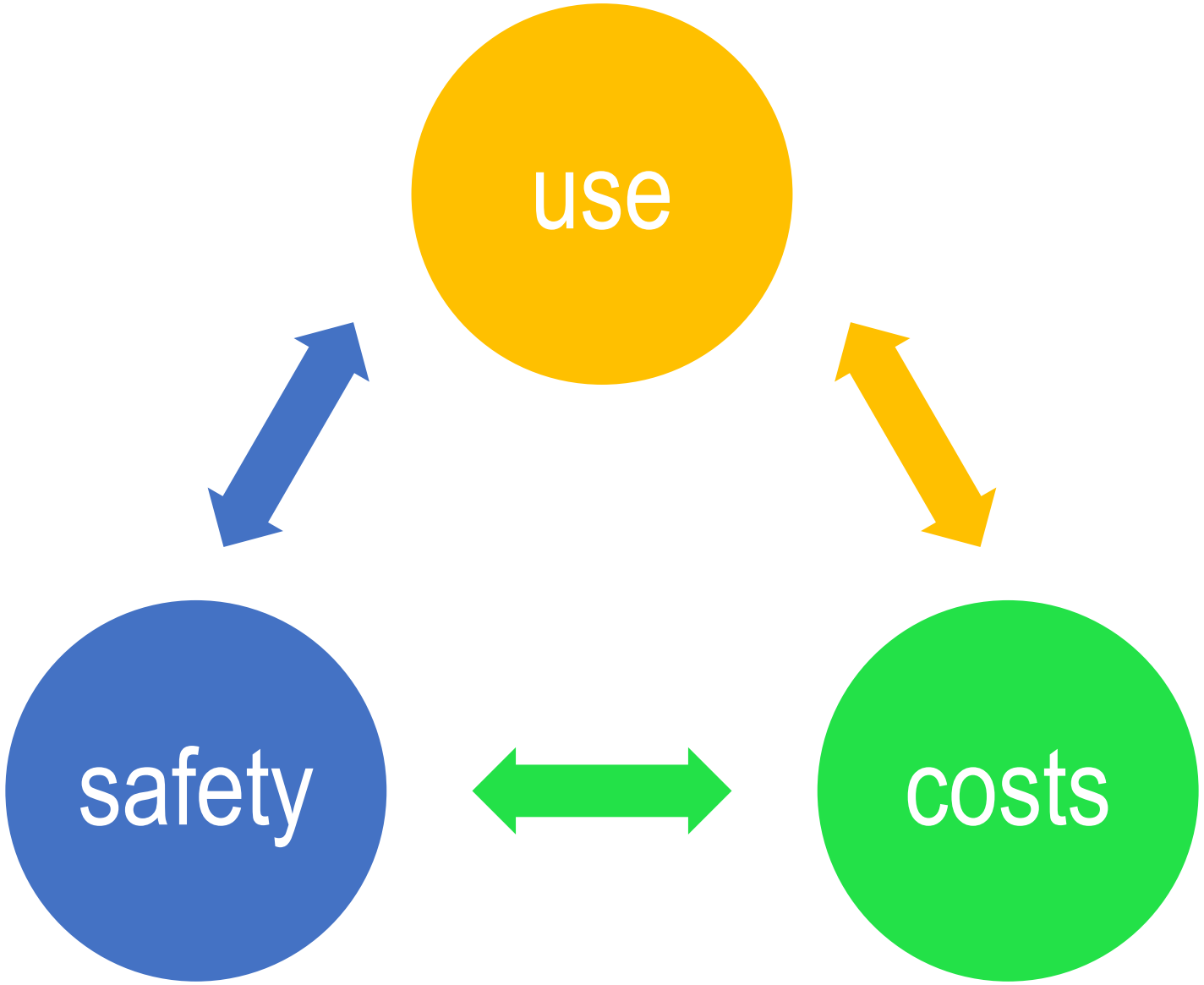
Bâtiment de l'Ile Feydeau, Nantes
foundation mouvement



deflection of flat roof leading to water accumulations

structural failure lead to important consequences

performance and design



performance and design

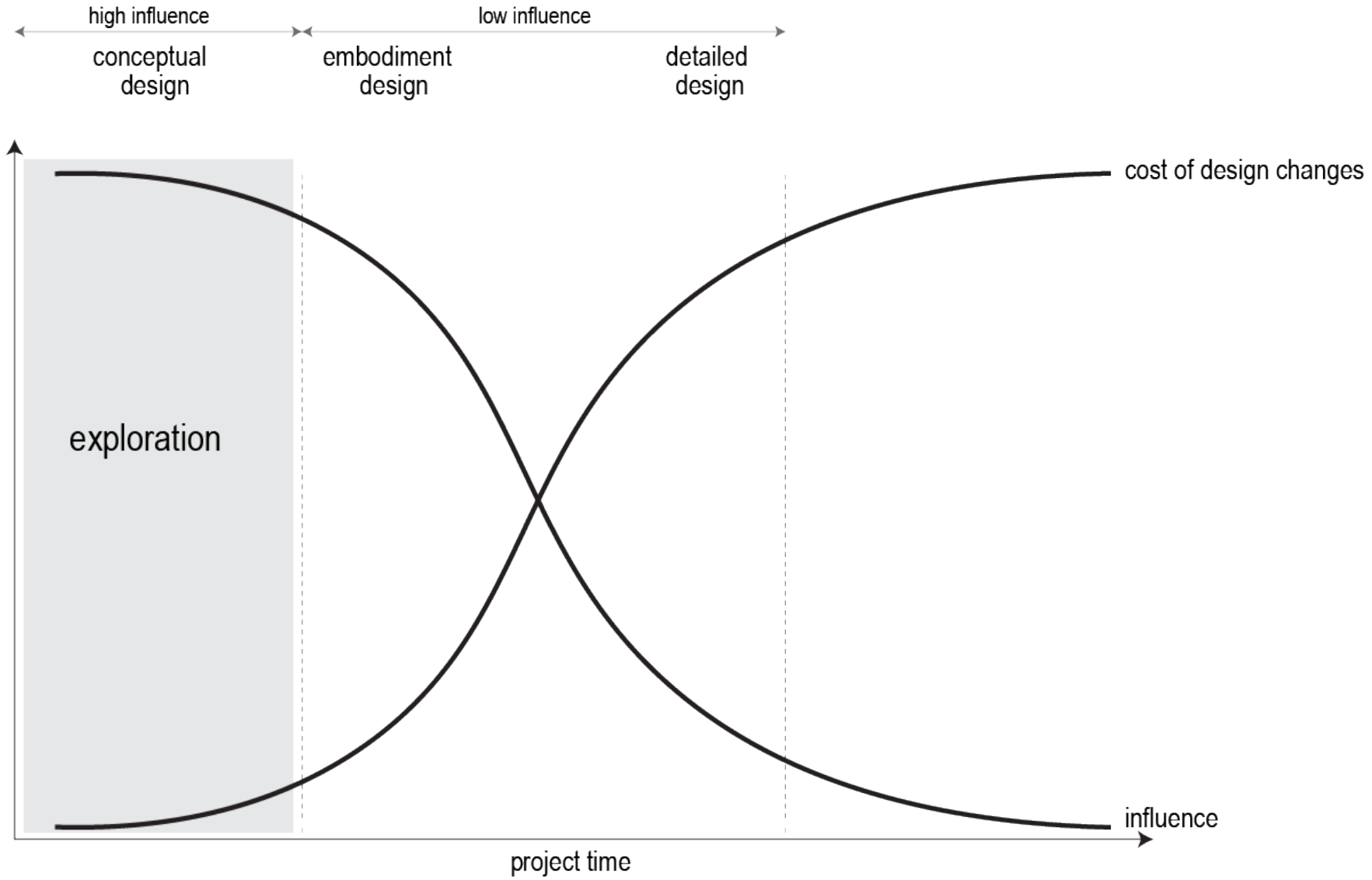
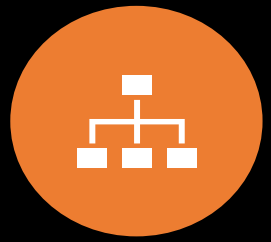


Figure: © Warmuth, EPFL, 2024 after Paulson, 1976. Designing to reduce construction costs

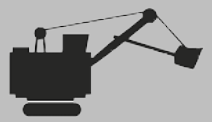


IMPACTS OF STRUCTURES

LIFE PHASES

PRODUCTION

supply



manufacturing

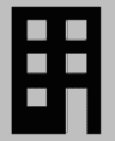
CONSTRUCTION

transport

construction

USE

maintenance/refurbishment

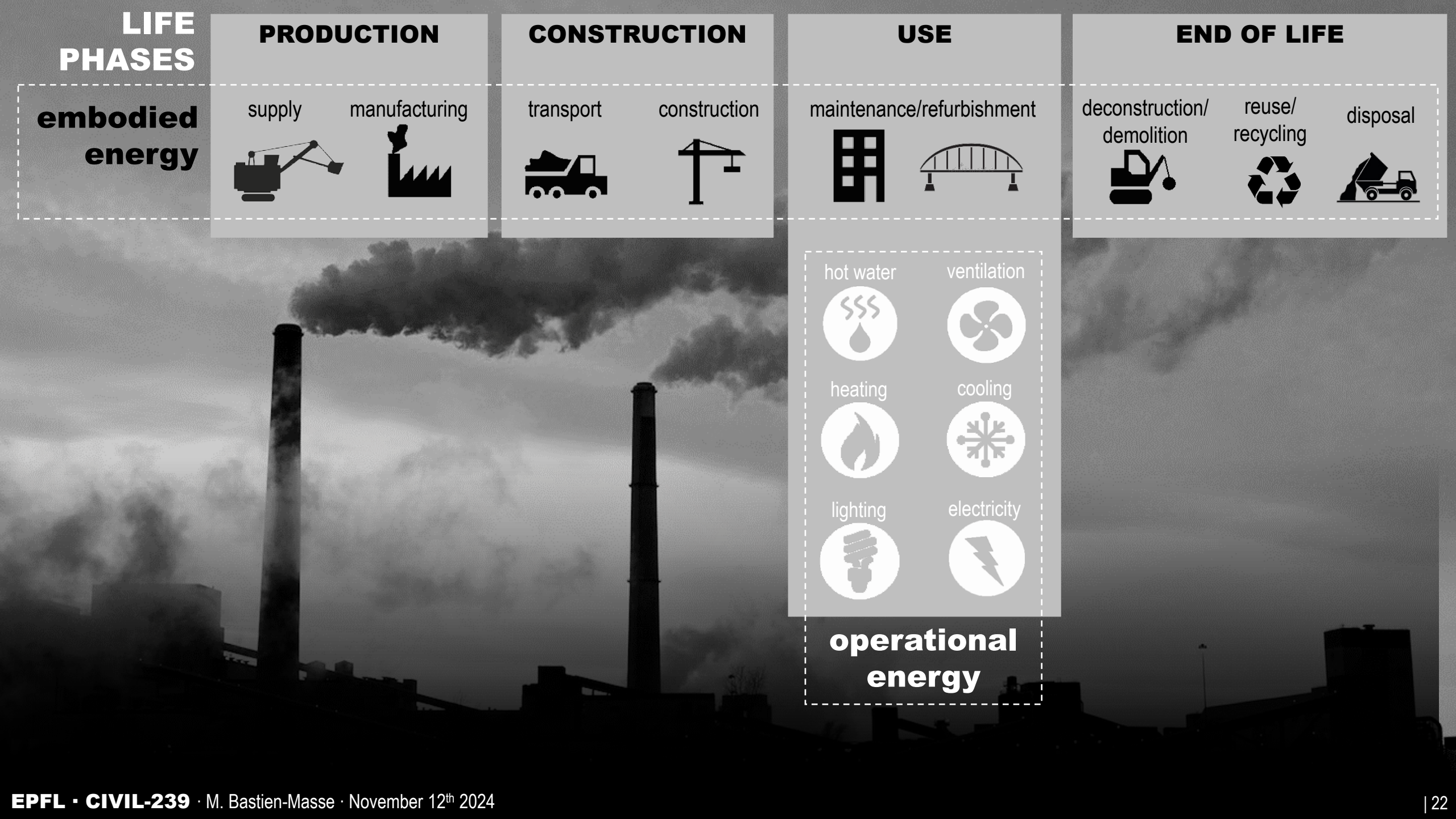


END OF LIFE

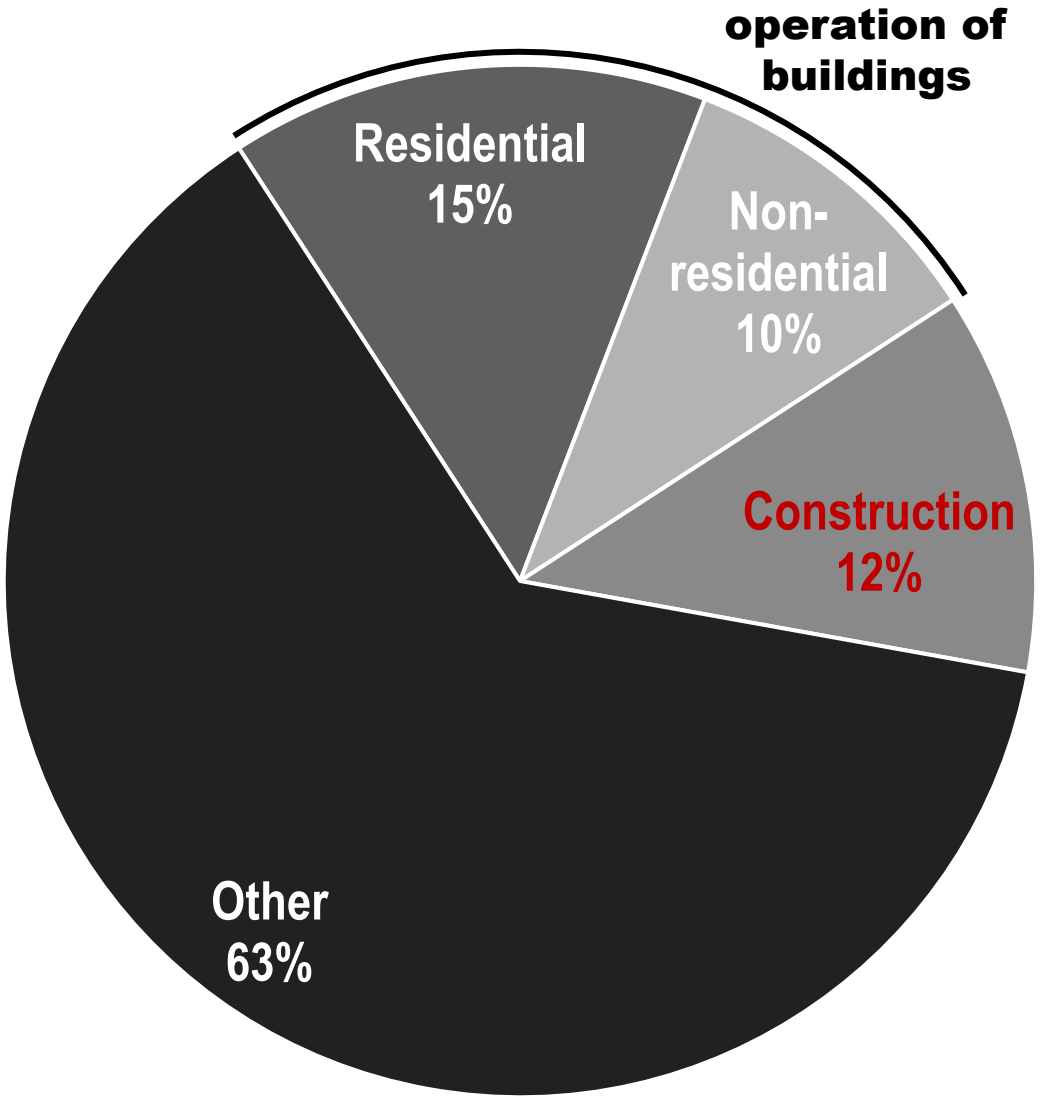
deconstruction/ demolition

reuse/ recycling

disposal

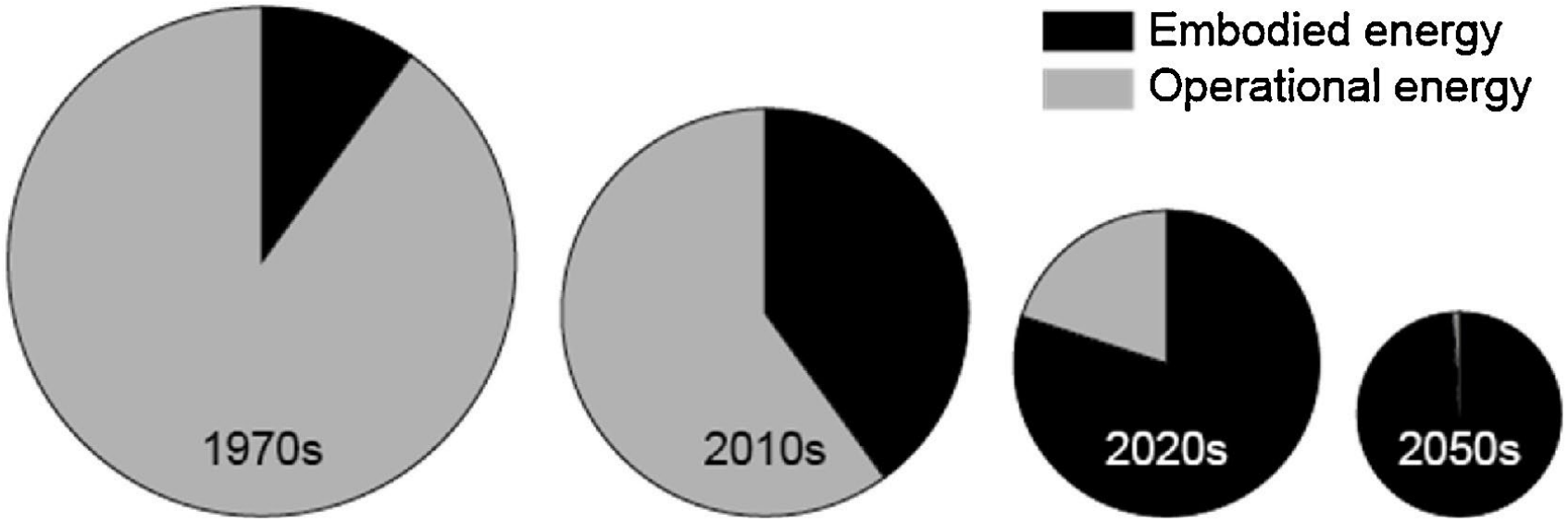

LIFE PHASES
PRODUCTION
CONSTRUCTION
USE
END OF LIFE
embodied energy
supply
manufacturing
transport
construction
maintenance/refurbishment
deconstruction/ demolition
reuse/ recycling
disposal
hot water
ventilation
heating
cooling
lighting
electricity
operational energy

anthropogenic global CO_2 emissions



Global Status Report for Buildings and Construction 2024-2025 · p.31 · UNEP · 2025

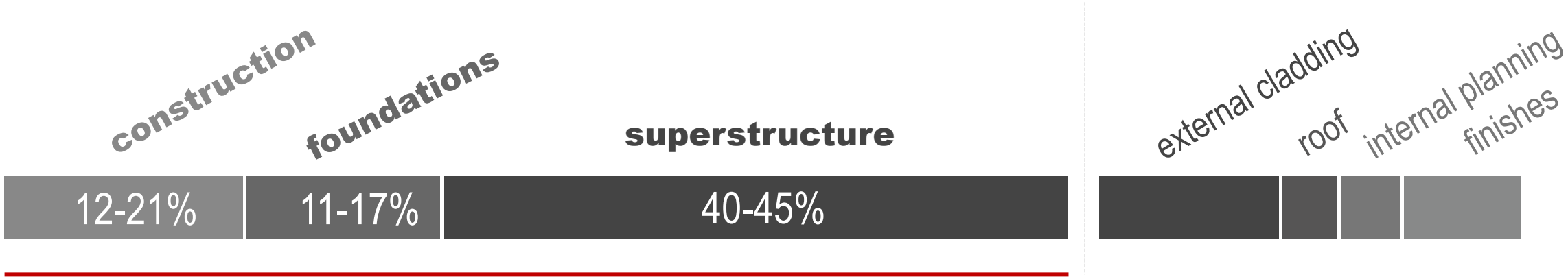
embodied energy due to buildings



Orr et al. 2019. Minimising energy in construction: Practitioners' views on material efficiency, Resources, Conservation and Recycling, https://doi.org/10.1016/j.resconrec.2018.09.015

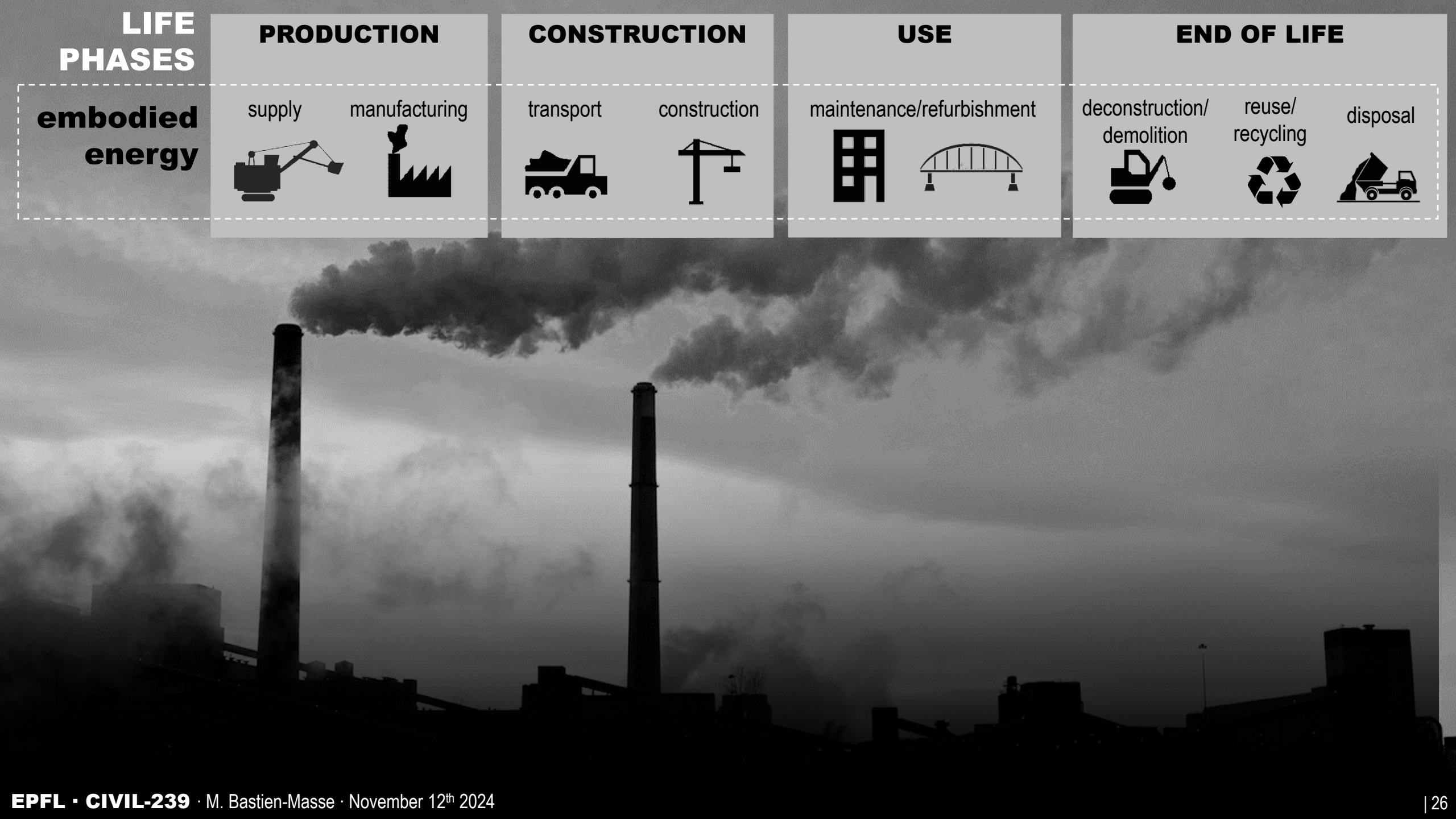
embodied CO_2 of load-bearing structures

cradle-to-gate



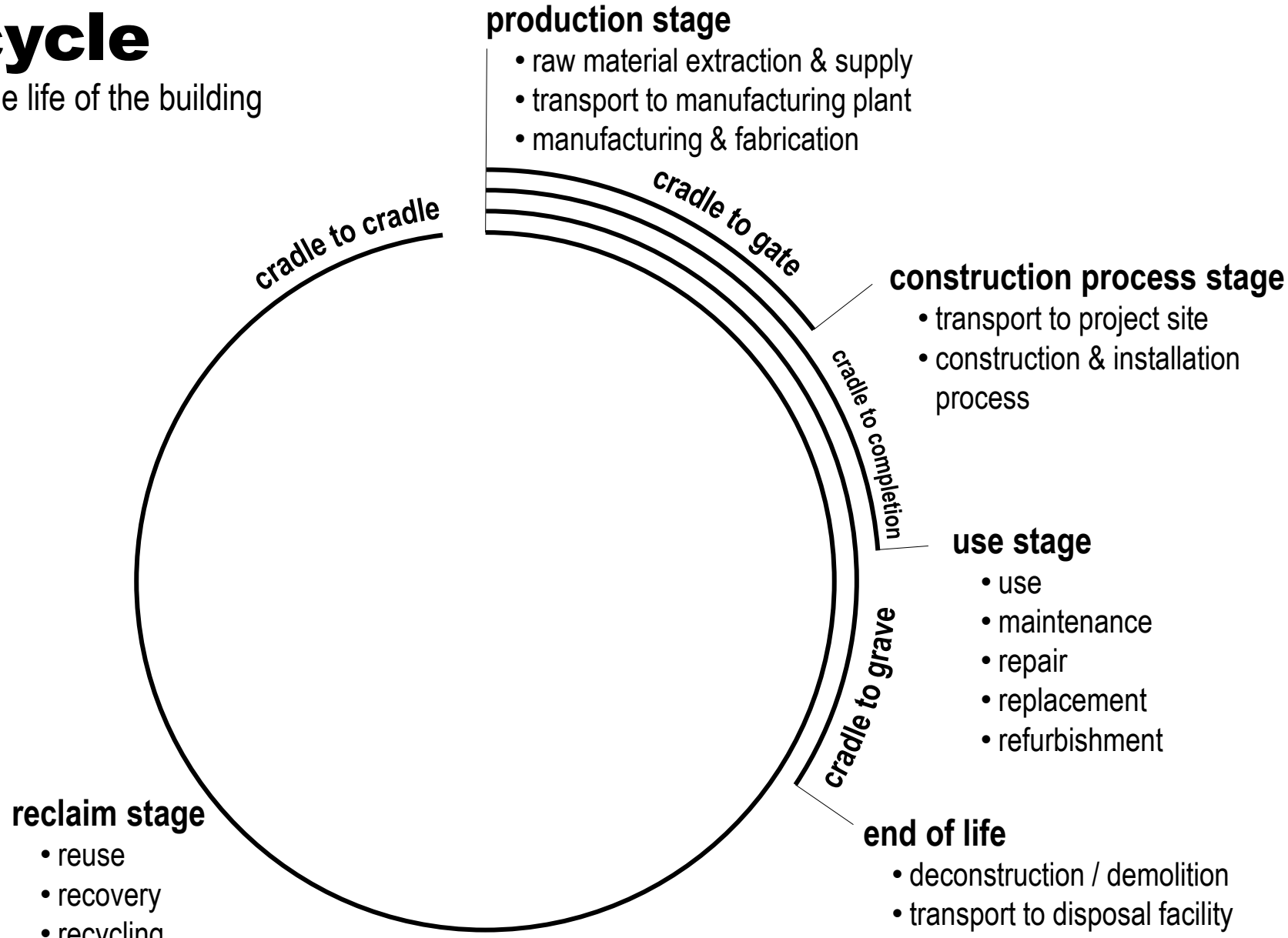
Embodied CO2 of structural frames · S.Kaethner & J.Burridge · The Structural Engineer, London, United Kingdom, pages 33-40 · 2012

LIFE PHASES	PRODUCTION		CONSTRUCTION		USE		END OF LIFE		
embodied energy	supply	manufacturing	transport	construction	maintenance/refurbishment		deconstruction/ demolition	reuse/ recycling	disposal



building life-cycle

consecutive and linked phases in the life of the building

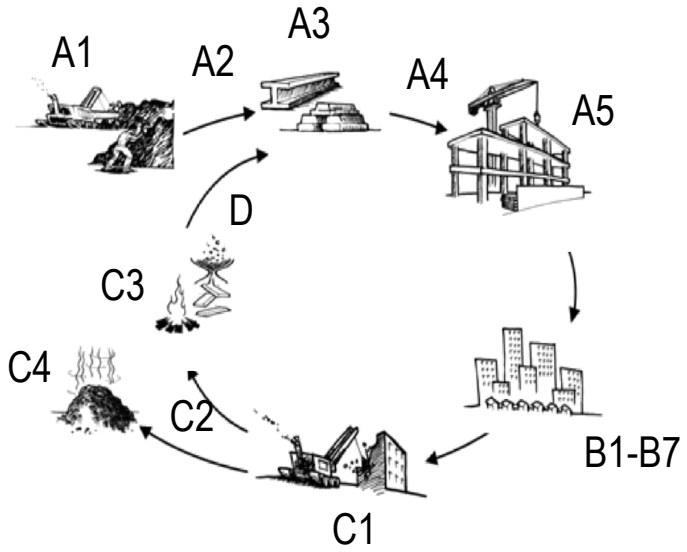


after International LCA standard ISO 14040 (see also EN 15978 & SIA2032:2020)

Figure: © EPFL, 2022

building life-cycle

consecutive and linked phases in the life of the building



Building life-cycle information

product stage

- A1 · raw material supply
- A2 · transport
- A3 · manufacturing

construction process stage

- A4 · transport
- A5 · construction/installation processes

use stage

- B1 · use
- B2 · maintenance
- B3 · repair
- B4 · refurbishment
- B5 · replacement
- B6 · operational energy use
- B7 · operational water use

end of life stage

- C1 · deconstruction/demolition
- C2 · transport
- C3 · waste processing
- C4 · disposal

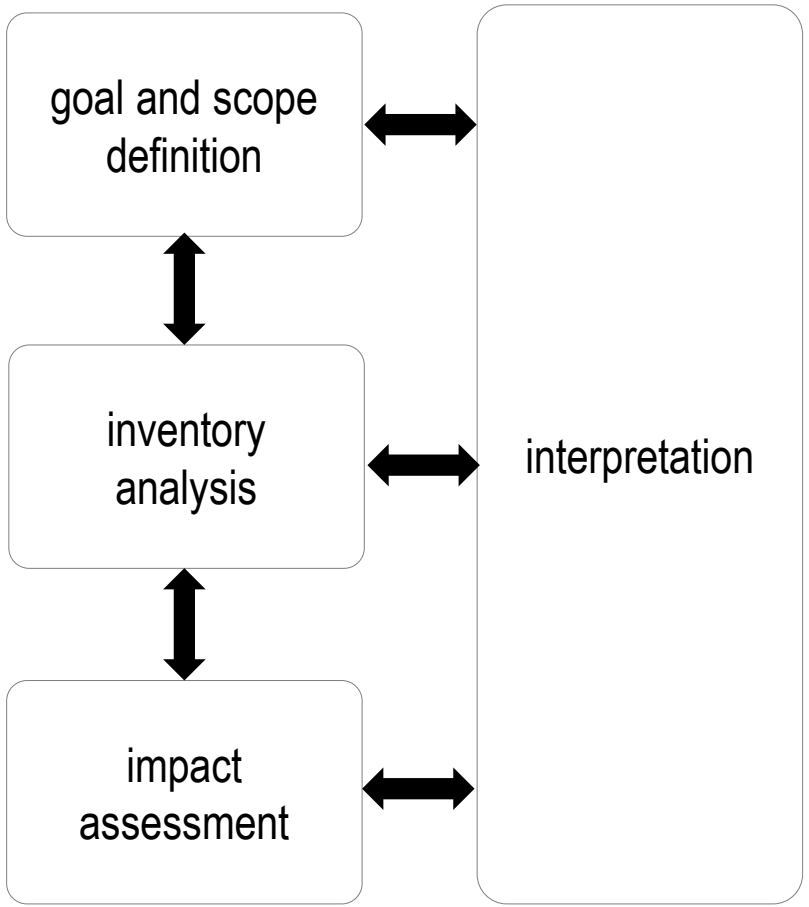
supplementary information beyond the building life cycle

benefits and loads beyond the system boundary

- D · reuse, recovery, recycling

International LCA standard ISO 14040 (see also EN 15978 & SIA 2032:2020)

life-cycle assessment framework



How?

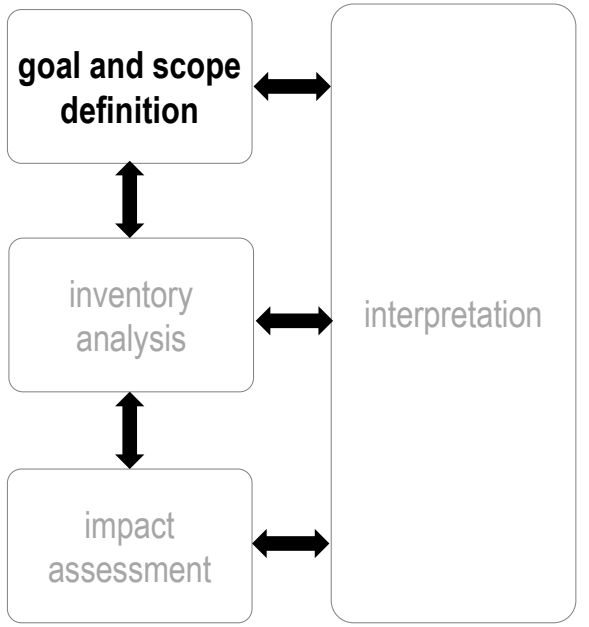
- compiling an inventory of relevant inputs and outputs
- evaluating the potential environmental impacts associated with those inputs and outputs
- interpreting the results in relation to the objectives of the study

Why?

- validating (or infirming) assumptions based on values
- quantifying environmental impacts
- **comparing solutions**

"Life Cycle Assessment in the Built Environment", R. Crawford, 2011
Figure: © Kupfer et Fivet, 2025

goal

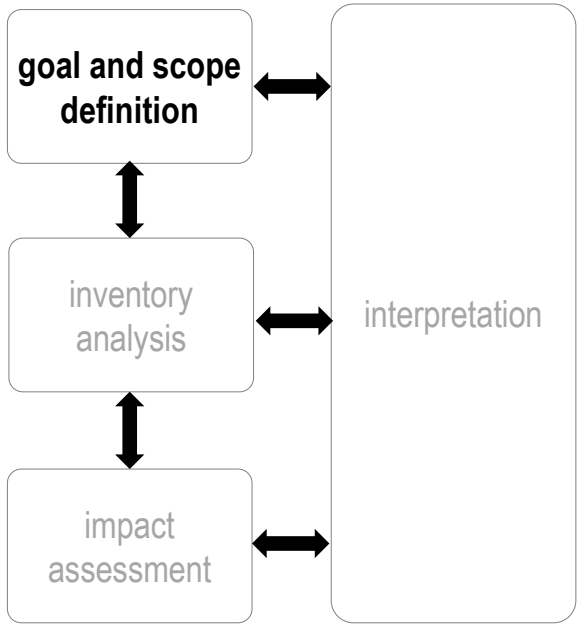


describes **what** is being measured and what the measurements will be used for (**why**)

to compare the carbon footprint of the construction of two new office-building designs

to inform a client about the design environmental impacts in terms of global-warming potential

functional unit



› functional unit

Quantified function fulfilled by the product

the construction of 1000 m² of office space, in Switzerland, in a 6-storey office building, in 2025

› functional equivalent

- Allows precise and unambiguous characterization of the object under study
- Constitutes the common denominator between different products, useful for comparing their impacts

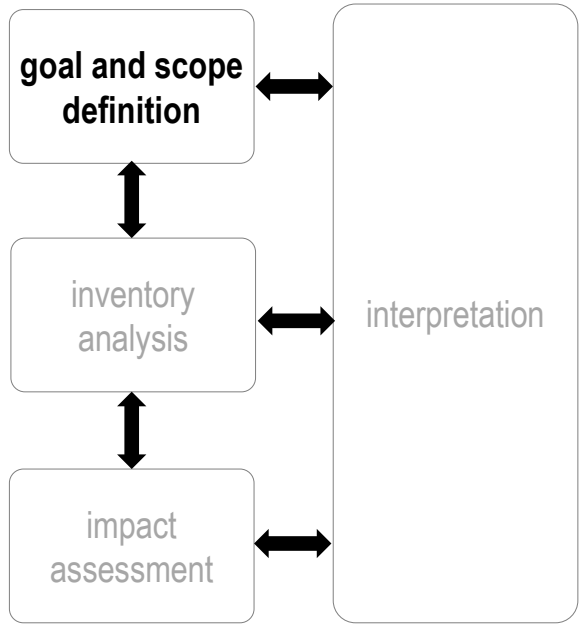
The construction of…

1000 m^2 of office space

or

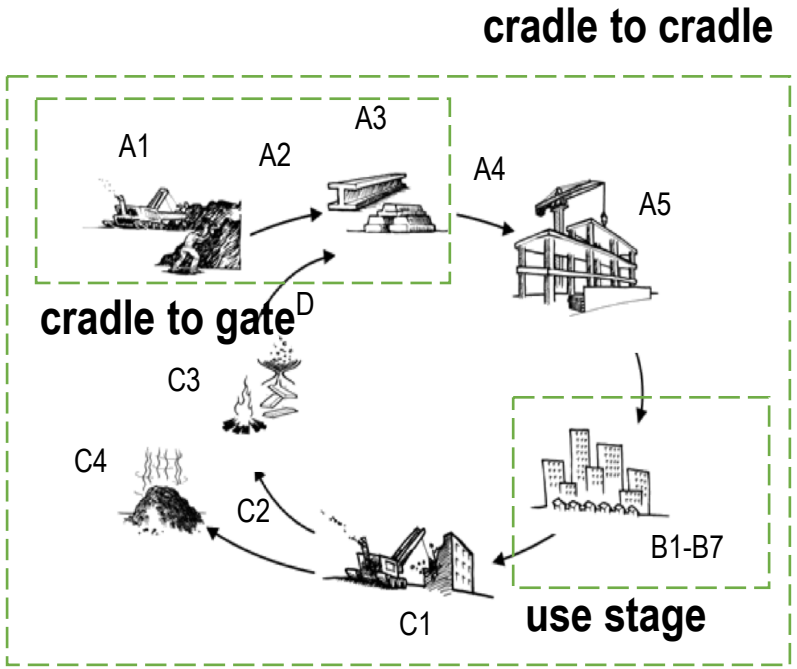
50 office desks (including needed bathrooms, cafeteria and reception area)

system boundaries

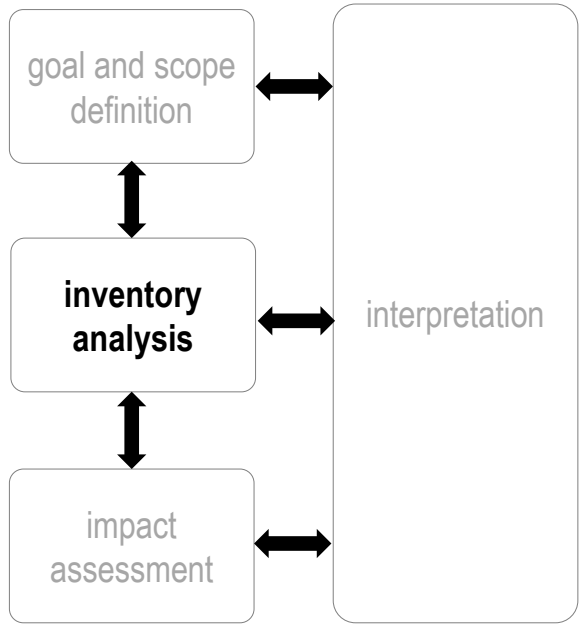


› system boundaries

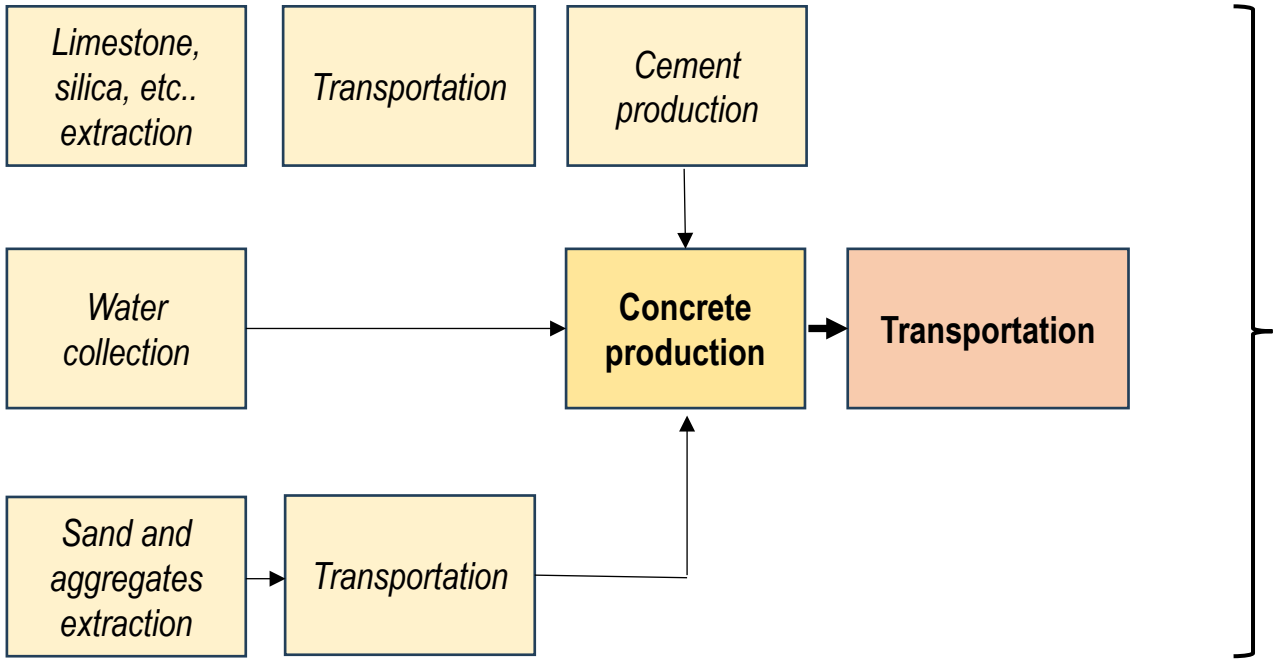
List of life-cycle stages and product function which are included or excluded from the comparison



impact factors



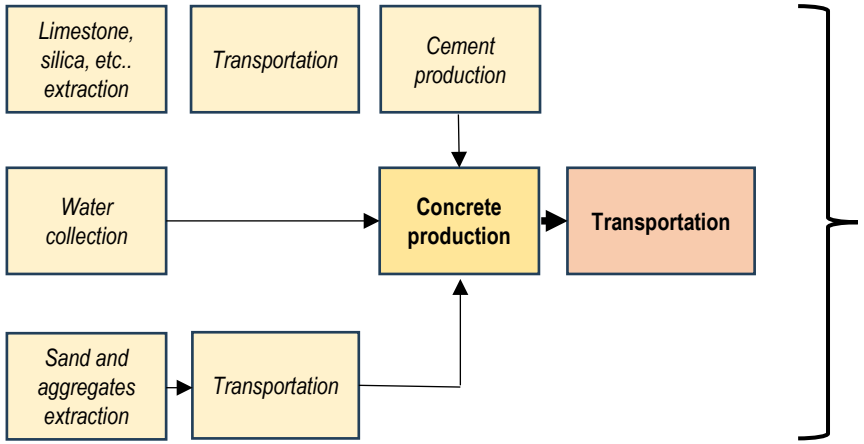
PRODUCTION stage



cradle-to-gate impact factor

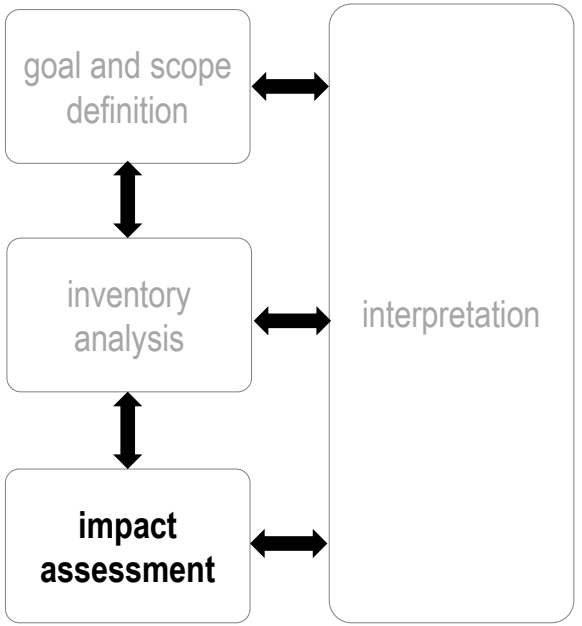
Units:
Indicator units / weight or volume of material

impact assessment



cradle-to-gate impact factor

Units: Indicator units / weight or volume of material



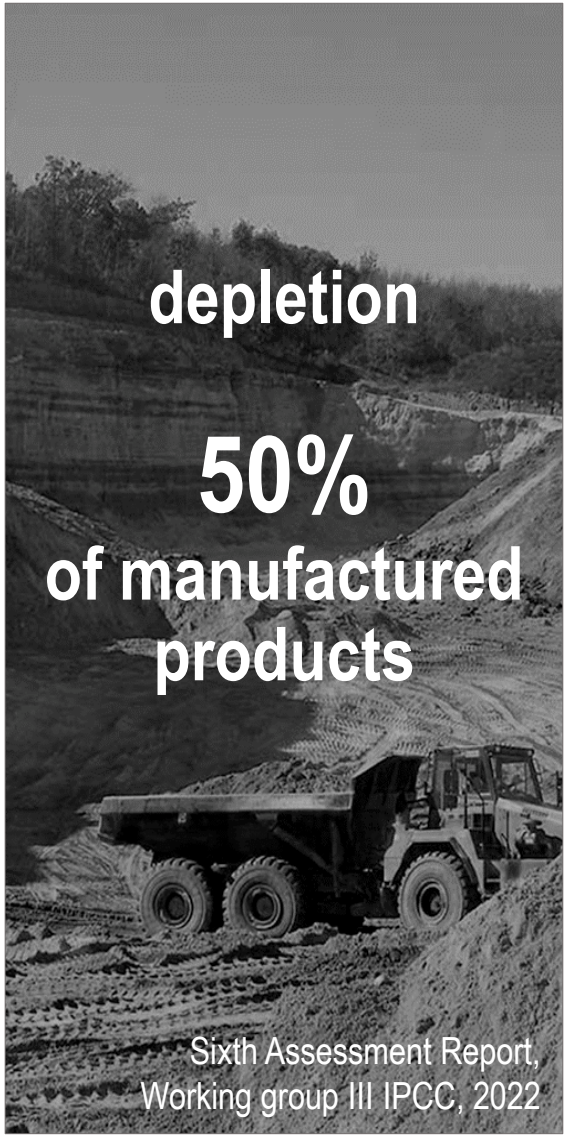
$$\sum_{i=1}^{n}$$

embodied carbon coefficient (ECC) $kg_{CO2eq} / kg_{material}$ X material quantity $kg_{material}$ = global warming potential (GWP) kg_{CO2eq}

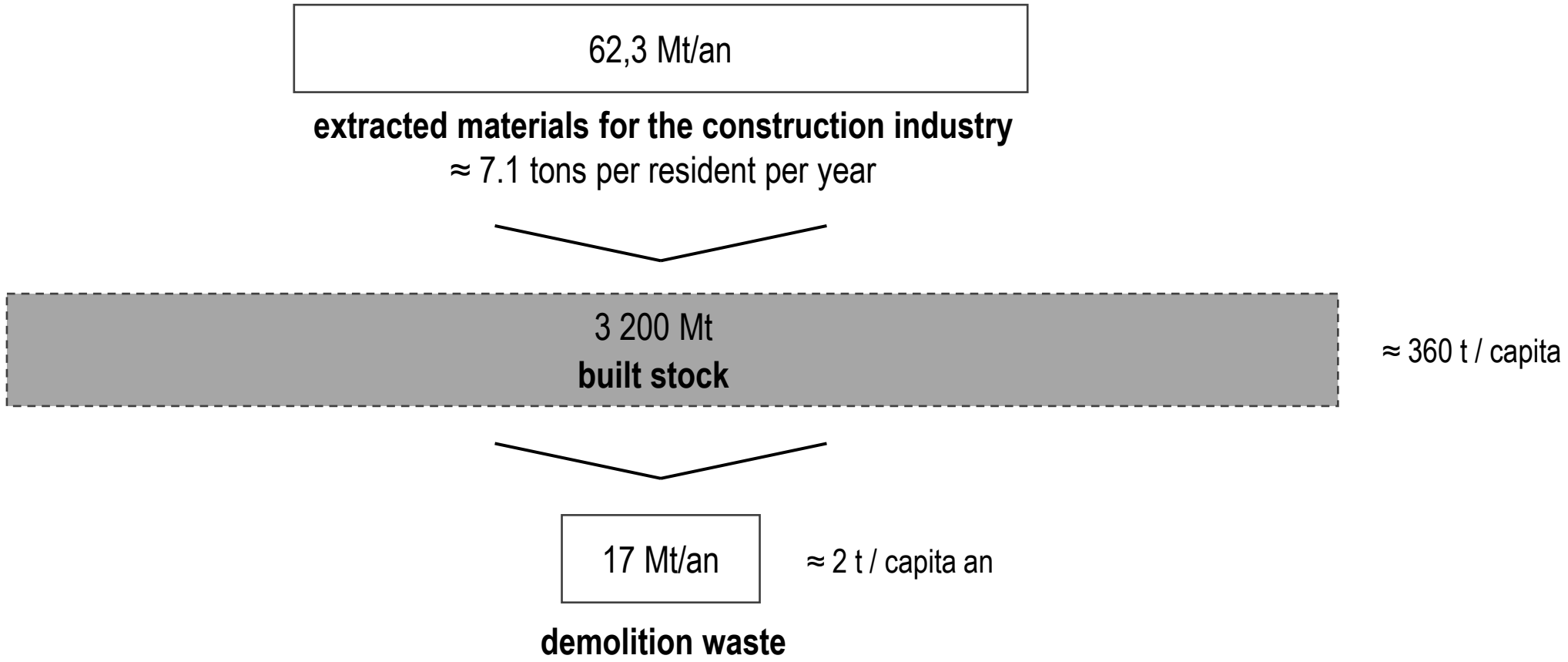
materials ↔ **structural typologie**

PRODUCTION stage

construction sector



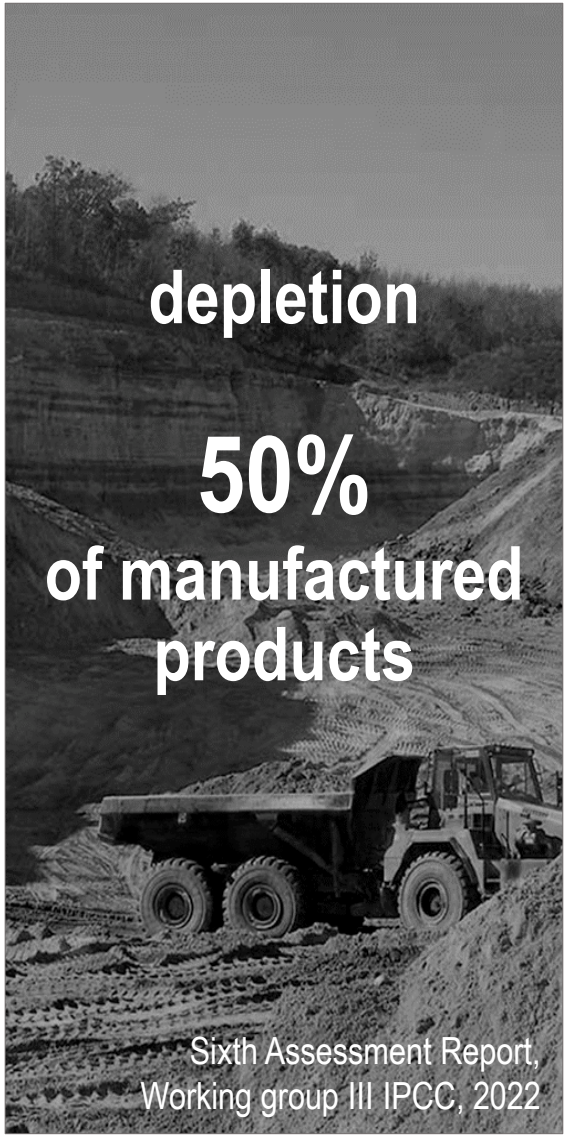
material extraction in Switzerland



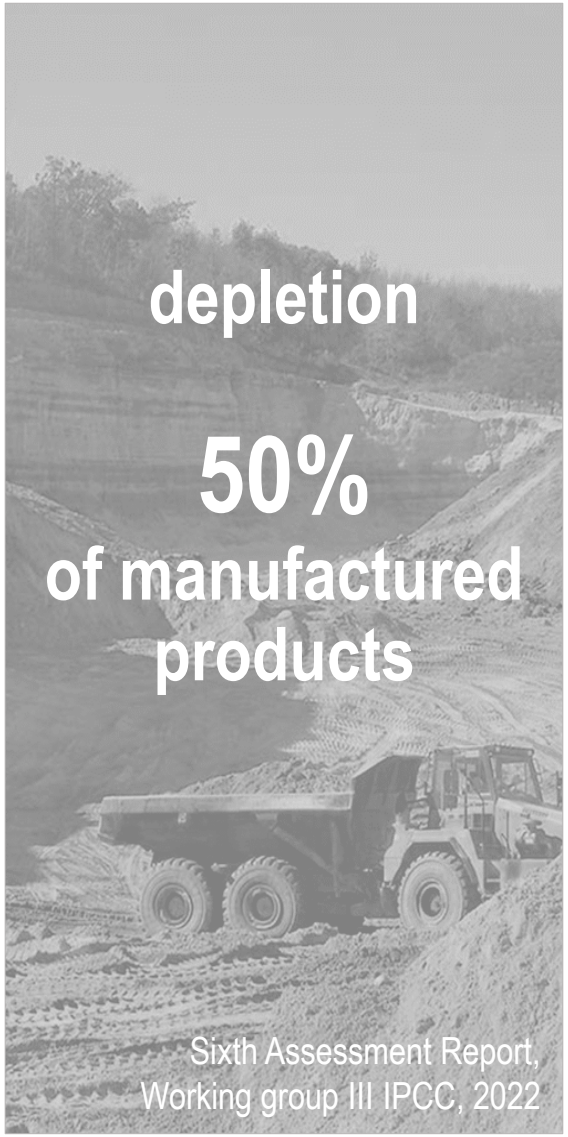
1 Mt (million tons) = 1 000 000 tons

OFEV (2022) Déchets et matières premières en bref (données de 2021)

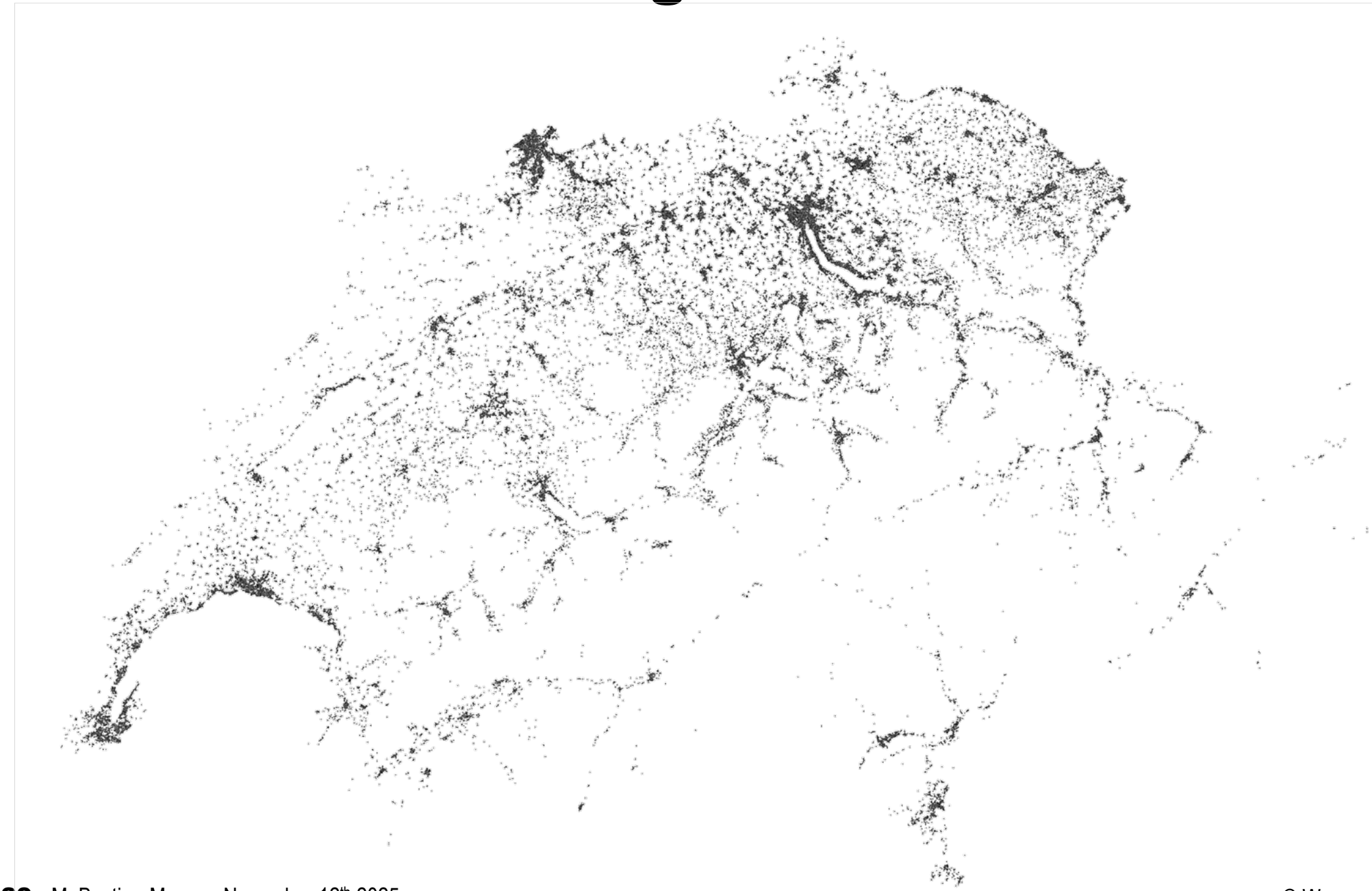
construction sector



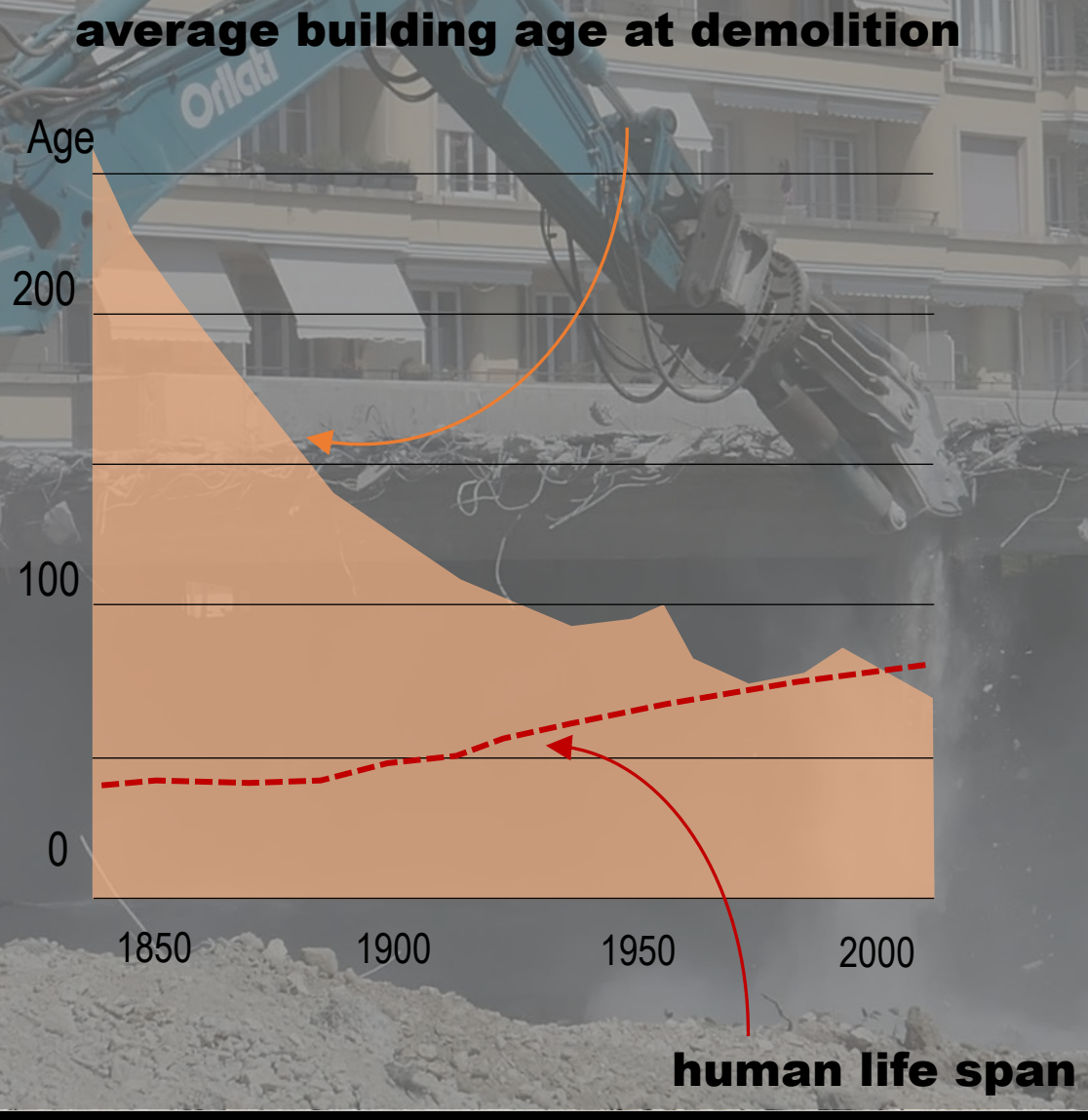
construction sector



70’000 demolished building between 2000 et 2022

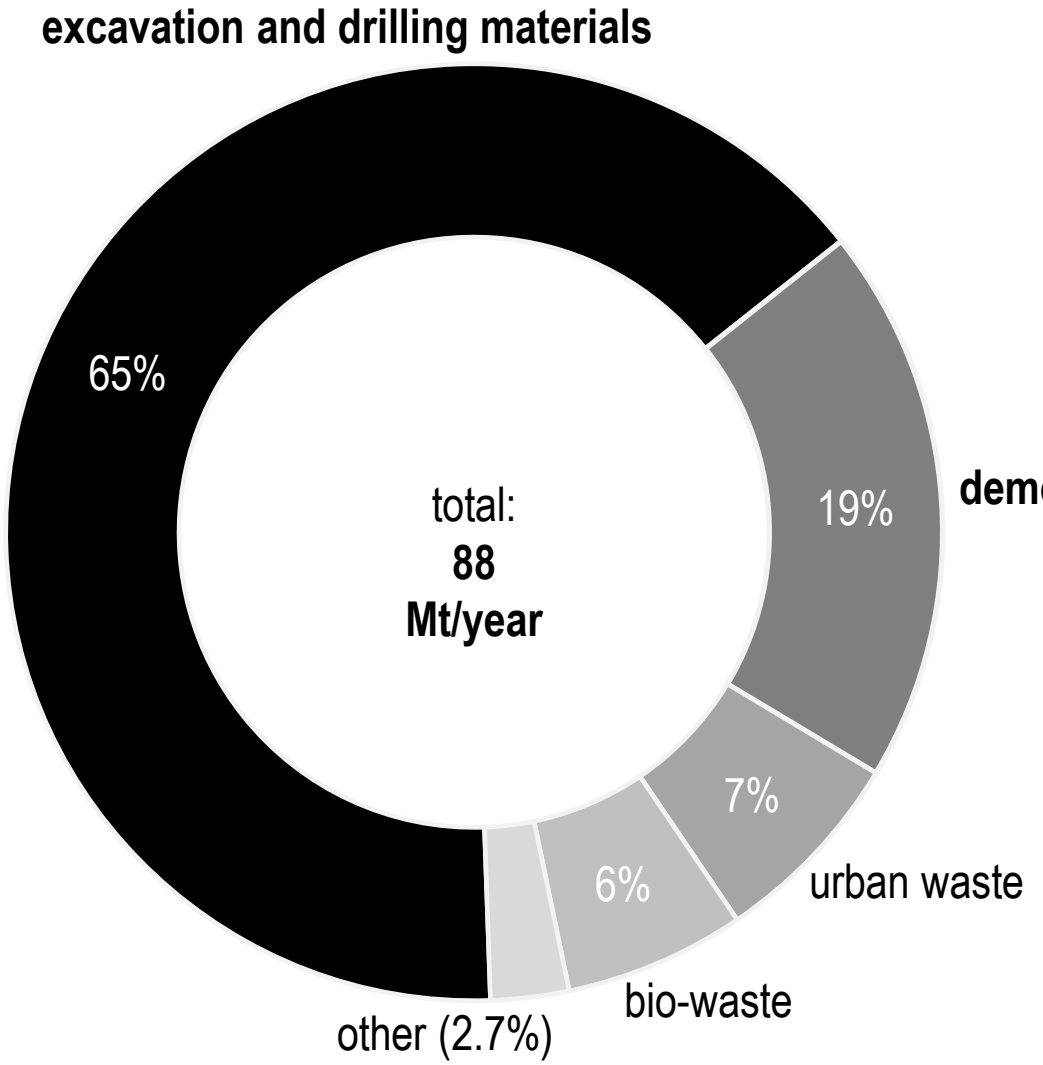


evolving needs



Aksözen et al. 2017. Mortality analysis of an urban building stock. Building Research & Information, https://doi.org/10.1080/09613218.2016.1152531

waste in Switzerland



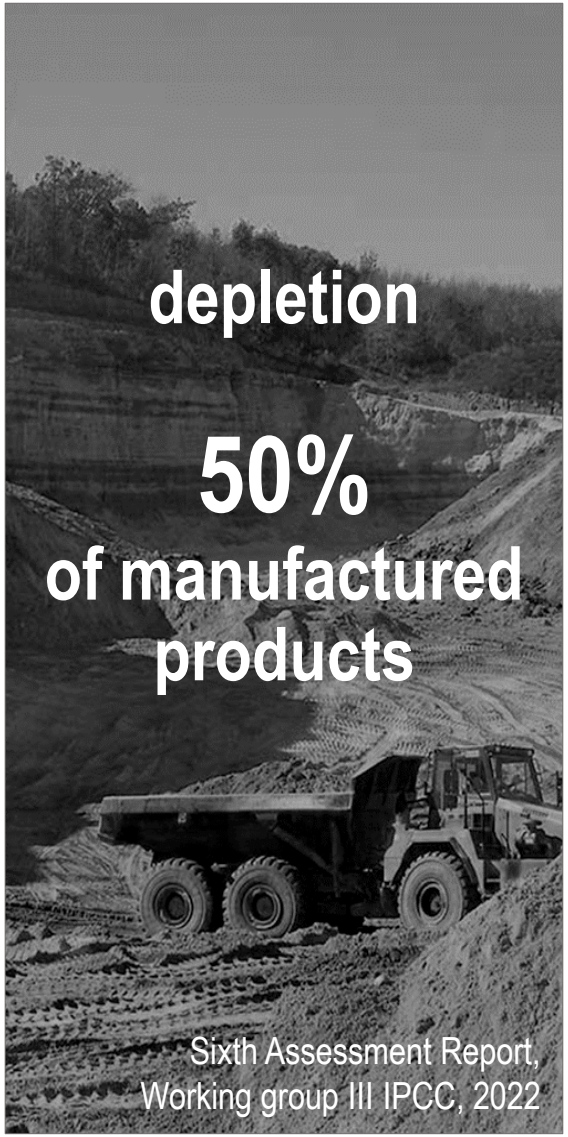
demolition waste

› 12 Mt/year recycled
› 5 Mt/year landfilled or incinerated

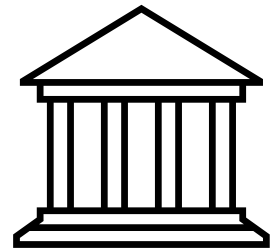
1 Mt (million tons) = 1 000 000 tons

OFEV (2022) Déchets et matières premières en bref (données de 2017)
Figure: © Fivet, EPFL, 2023

construction sector



regulations



Switzerland:

› **CO_2 Act:** GHGE reduced by 50% by 2030 compared to 1990 levels

› **Climate and Innovation Act:** Net-zero emissions by 2050 (voted in 2023)

› **Environmental Protection Act:**

Preserve natural resources use and reduce environmental impacts throughout the entire life cycle of products and buildings
Recycling prioritized over incineration
Promotes circular economy, including the use of environmentally friendly building materials and the reuse of building components

Geneva

› Inclusion of requirements regarding the carbon footprint of “significant” buildings in LCI (Loi sur les constructions et installations)

Zurich

› Constitutional article that mandates the creation of frameworks for:

Responsible use of resources and materials, closing material loops and promoting reuse and recycling in construction

→ *Many other cantons are currently working on new regulations to promote circular economy and sustainable building construction.*

standards

› **SIA 390/1:2025** (replaces SIA 2040:2017, emphasizing climate impact over solely energy efficiency in buildings)
La voie du climat – Bilan des gaz à effet de serre sur le cycle de vie des bâtiments
Klimapfad – Treibhausgasbilanz über den Lebenszyklus von Gebäuden
La via climatica – Bilancio dei gas serra per il ciclo di vita degli edifici

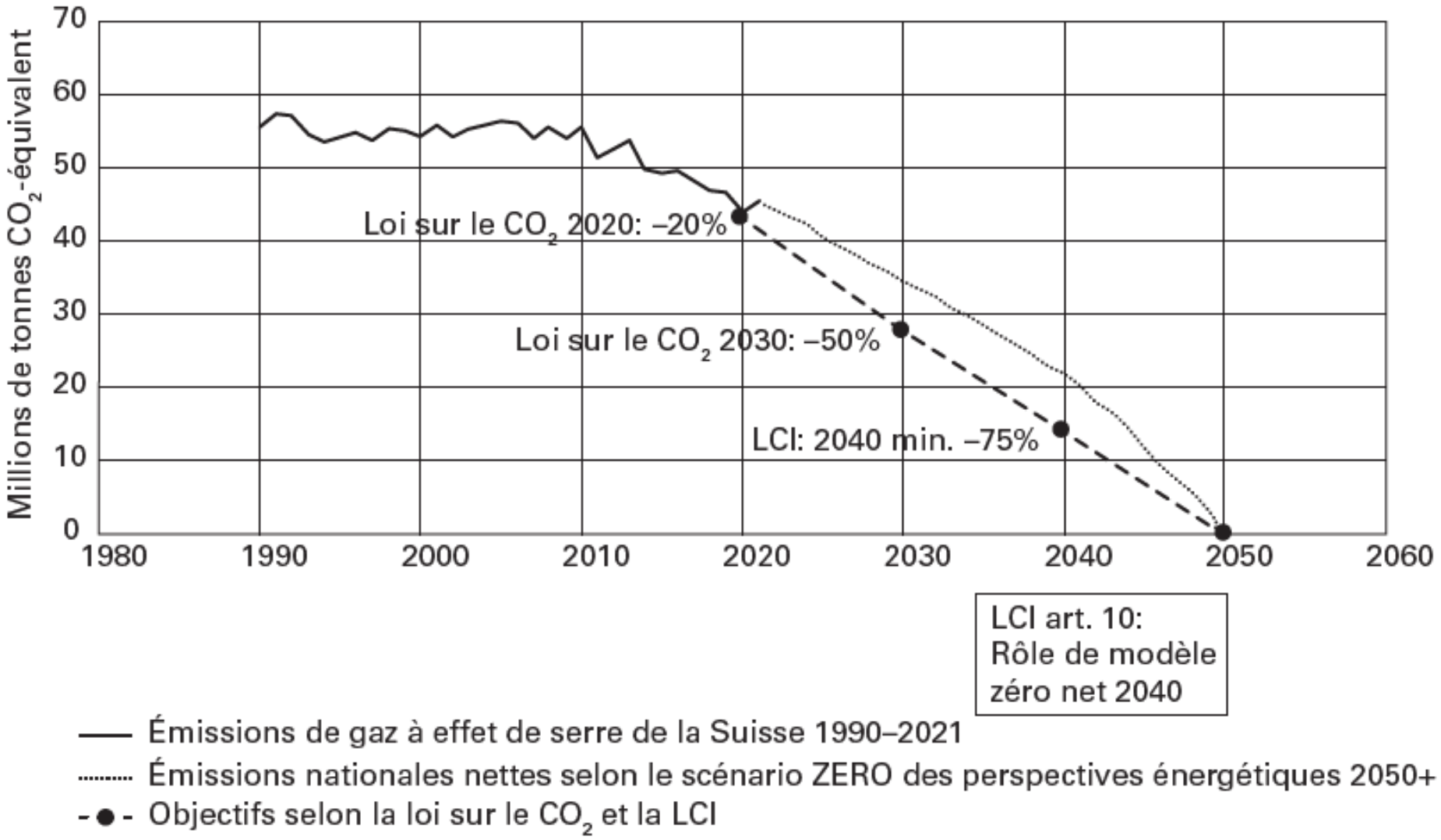
Goal: to support Switzerland's goal of achieving net-zero emissions by 2050
Purpose: Framework to evaluate and reduce GHGE in buildings' full life-cycle

Levels of GHGE per m^2 and per year (for a 60-year life cycle) :
- Base: 15 kg/m^2 (9 for construction)
- Ambitious: 10 kg/m^2 (6 for construction)

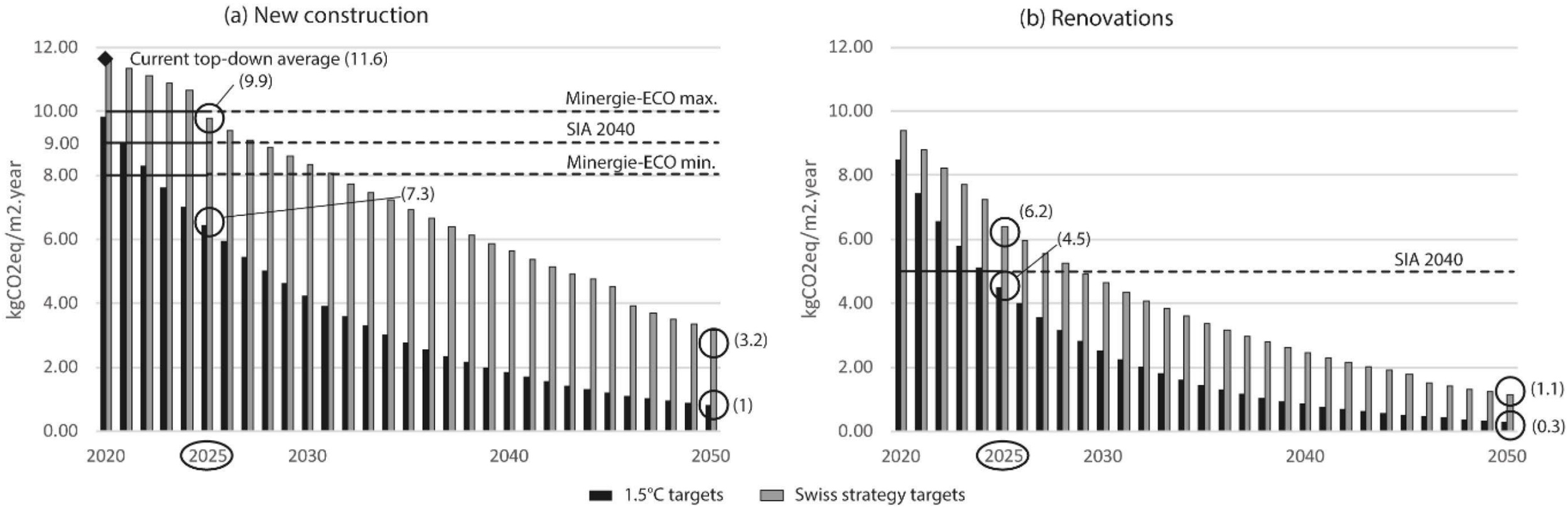
› **SIA 2032:2020**
L'énergie grise – Établissement du bilan écologique pour la construction de bâtiments
Graue Energie – Ökobilanzierung für die Erstellung von Gebäuden
Energia grigia negli edifici – Bilancio ecologico per la costruzione di edifici

› **EN 15804+A2 (2019) Environmental Product Declarations**
Rules for assessing and reporting environmental impacts of construction products

regulations

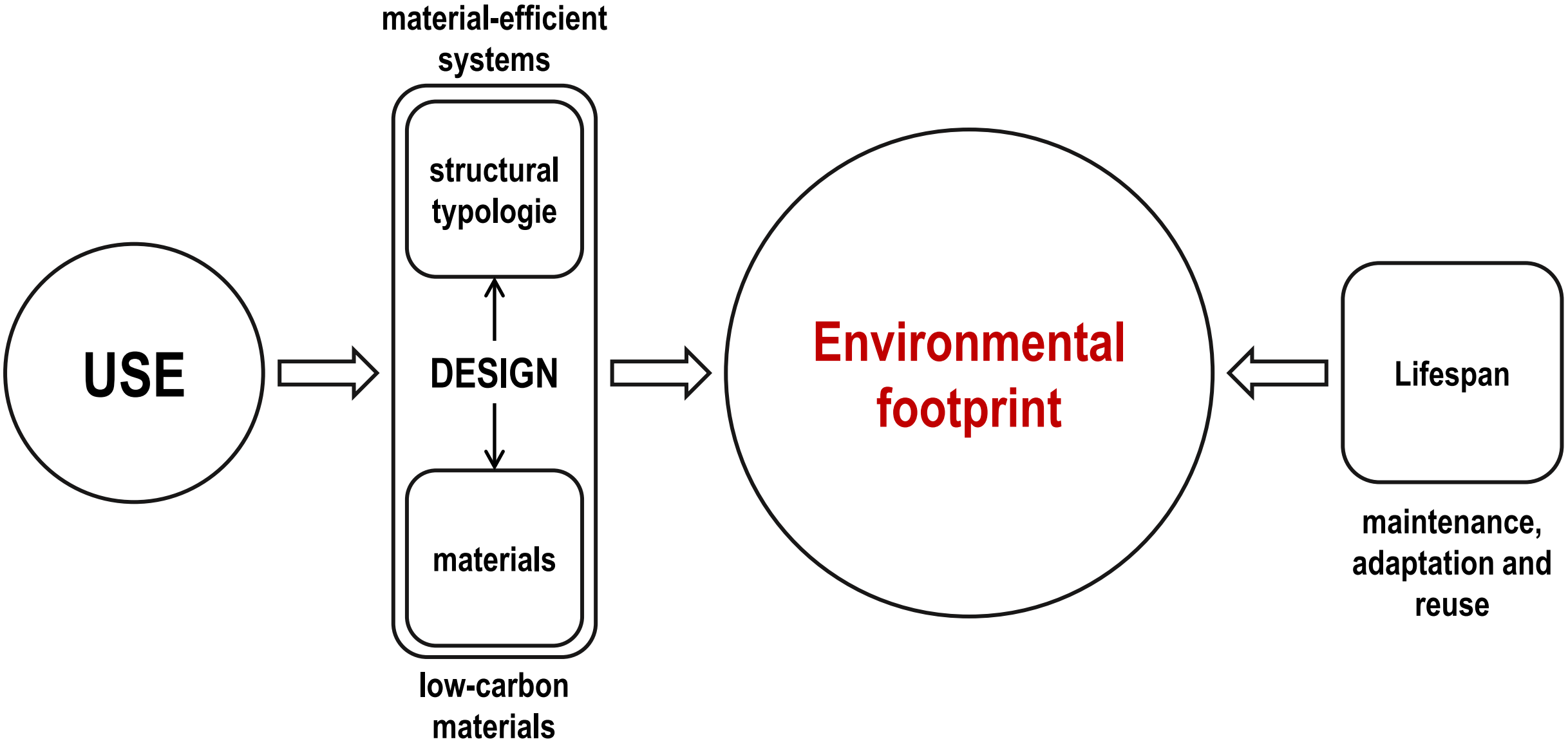


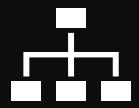
carbon budgets



Priore YD et al. 2023. Exploring the gap between carbon-budget-compatible buildings and existing solutions – A Swiss case study. Energy and Buildings, https://doi.org/10.1016/j.enbuild.2022.112598

strategies


material-efficient systems
structural typologie
USE
DESIGN
materials
low-carbon materials
Environmental footprint
Lifespan
maintenance, adaptation and reuse


MATERIALS

main structural materials

steel

reinforced concrete

timber

ECC vs material strength

Material	Description	ECC (kg_{CO2eq} / $kg_{material}$)	Strength (N/mm^2)	Density (kg/m^3)
Concrete C30/37	342 kg CEM I / m^3	0.12 – 0.14	f_{ck} = 30 N/mm^2 (compression)	2’400
Steel reinforcement B500B	Recycled from scrap	0.30 – 0.55	f_{sk} = 500 N/mm^2	7’850
Structural steel S235	Recycled from scrap, without surface coating	0.33 – 0.60	f_{yk} = 235 N/mm^2	7’850
Solid timber C24		0,13 – 0,47	f_{td} = 8.5 – 0.1 N/mm^2 (tension) f_{cd} = 12.4 – 1.8 N/mm^2 (compression)	500
Glued laminated timber GL24h		0.34 – 0.95	f_{td} = 12.8 – 0.15 N/mm^2 (tension) f_{cd} = 16.0 – 1.9 N/mm^2 (compression)	385

Regúlez et al. 2023. Sustainability in construction: The urgent need for a new ethics . Structural Concrete https://doi.org/10.1002/suco.202200406

SIA norms and

embodied global warming potential

$$\sum_{i=1}^{n}$$

embodied carbon coefficient (ECC)

$kg_{CO2eq} / kg_{material}$

X

material quantity

$kg_{material}$

=

global warming potential (GWP)

kg_{CO2eq}

inputs :

› geometry and actions

› material strength (f_d)
› material density (ρ)
› ECC

outputs :

› material volume
› material weight
› GWP

example

› Taking the maximum ECC, what is the GWP of this bar element?

1. if made of steel S235
2. If made of solid timber C24

Material	ECC (kg_{CO2eq} / $kg_{material}$)	Strength (N/mm^2)	Density (kg/m^3)
Structural steel S235	0.60	f_{yd} = 224 N/mm^2	7'850
Solid timber C24	0,47	f_{td} = 8.5 N/mm^2	500

GWP [kg_{CO2e}]

↳ **= ECC** [kg_{CO2eq}/kg] × **weight** [kg]

↳ **= density** [kg/m^3] × **volume** [m^3]

↳ **= bar length** [m] × **cross-section area** [m^2]

↳ **= action** [kN] / **strenght** [kN/m^2]

example

- Steel S235:
  - Cross-section area = 100kN / 235 N/mm^2 = 425 mm^2
  - Volume = 425 mm^2 x 1000 mm = 425'000 mm^3
  - Weight = 425'000 mm^3 x 7'850 kg/m^3 = 3.3 kg
  - GWP = 3.3 kg x 0.6 kg_{CO2eq}/kg = **2 kg_{CO2eq}**

- Solid timber C24
  - Cross-section area = 100kN / 8.5 N/mm^2 = 11'765 mm^2
  - Volume = 11'765 mm^2 x 1000 mm = 11'765'000 mm^3
  - Weight = 11'765'000 mm^3 x 500 kg/m^3 = 5.9 kg
  - GWP = 5.9 kg x 0.47 kg_{CO2eq}/kg = **2.8 kg_{CO2eq}**

alternatives : bio-based material

load-bearing straw bale construction

rebuiLT student project
https://rebuilt.cargo.site/
© PJRenaud – rebuiLT, 2023

ECO 46, Lausanne
© CArPE, 210-2012

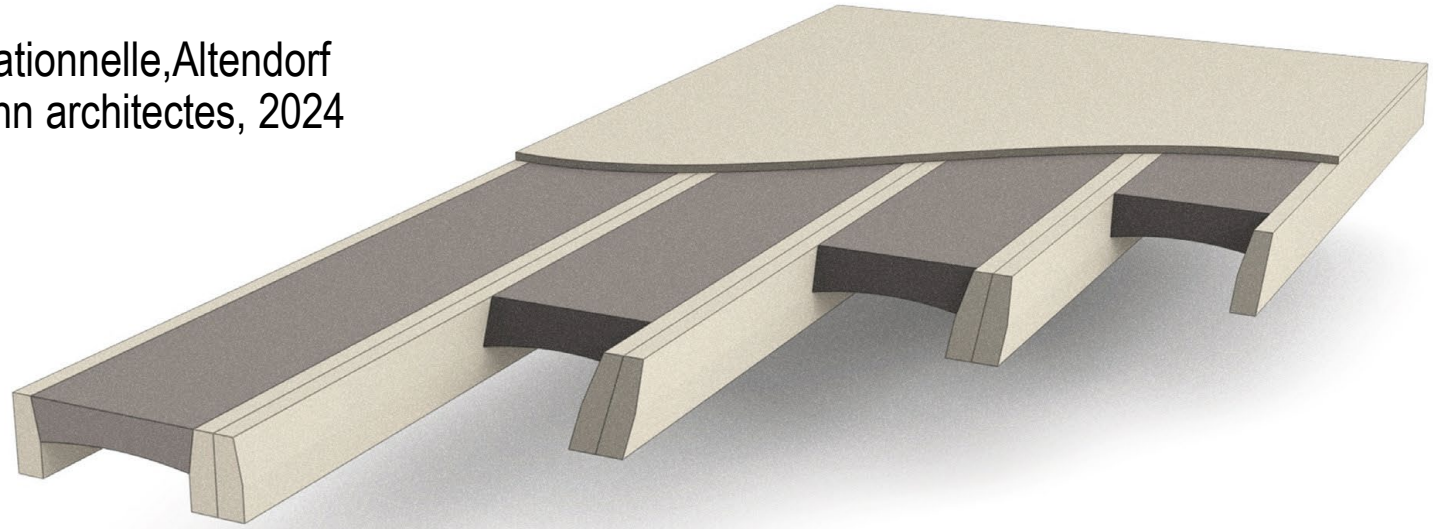
alternatives: geo-based materials

rammed earth construction

Rammed earth walls
Ricola Kräuterzentrum
Herzog & De Meuron, 2014

Earth bircks, aerth and timber slabs (Rematter®)
Maison intergénérationnelle,Altendorf
Jomini Zimmermann architectes, 2024

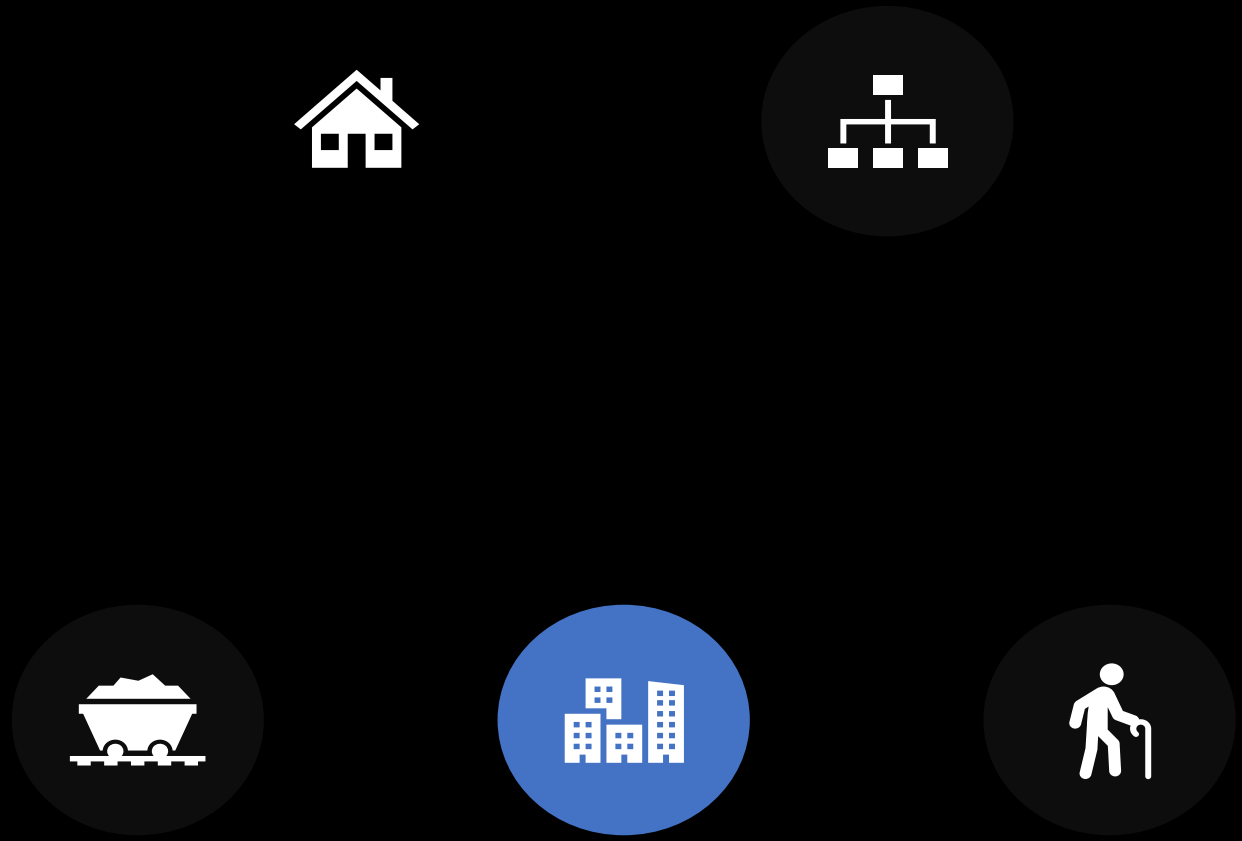
Rematter® floor slabs
3-Layer Wood Panel
Solid Timber Beam
Rammed Earth



alternatives: geo-based materials

massiv stone masonry

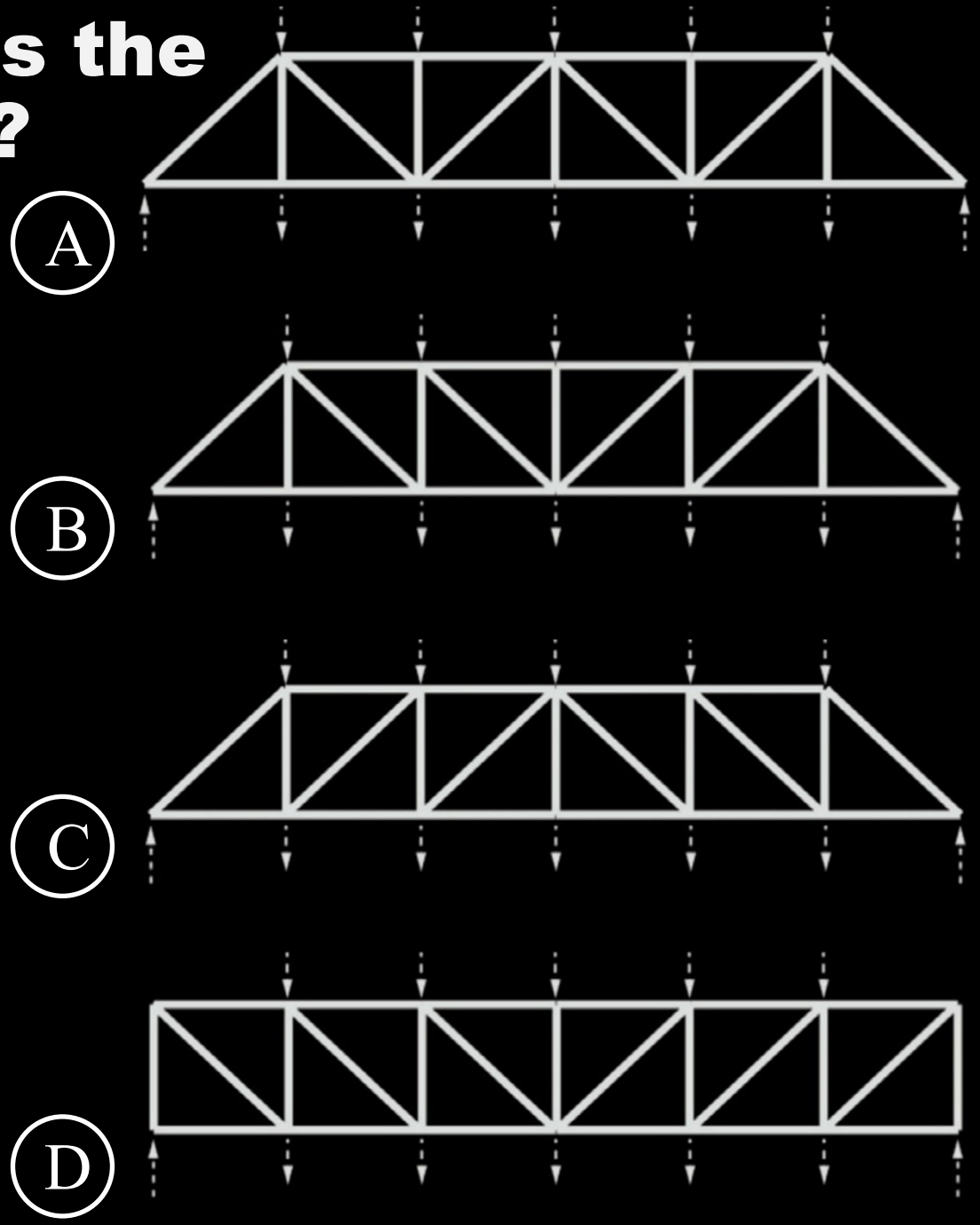
Immeubles de logements, Arch. Archiplein et Gilles Perraudin Architecte, Plan les Ouates, 2020


STRUCTURAL
SYSTEMS

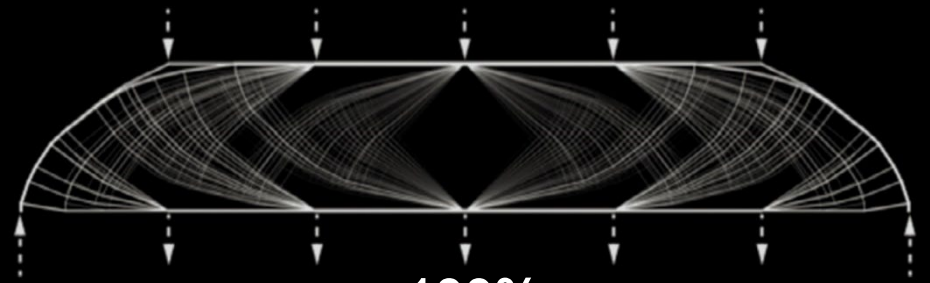
structural topology

POLL: what topology requires the greatest amount of material?

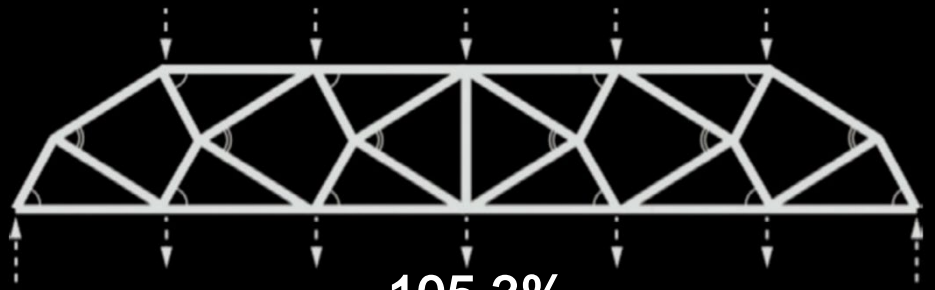
Join at
slido.com
#2474112



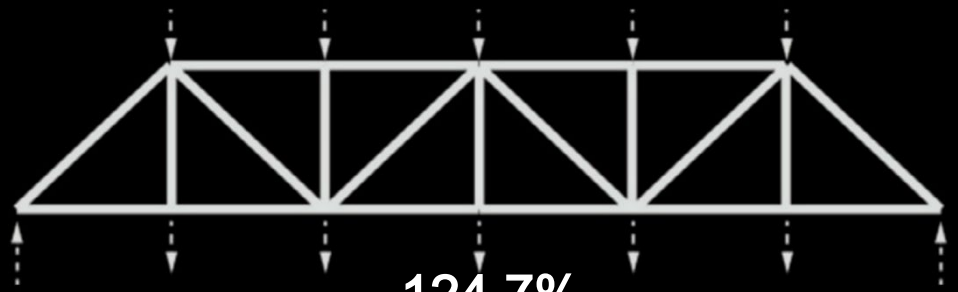
structural topology



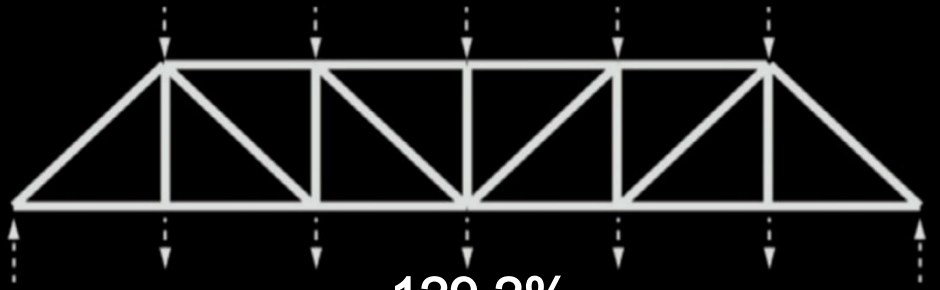
100%



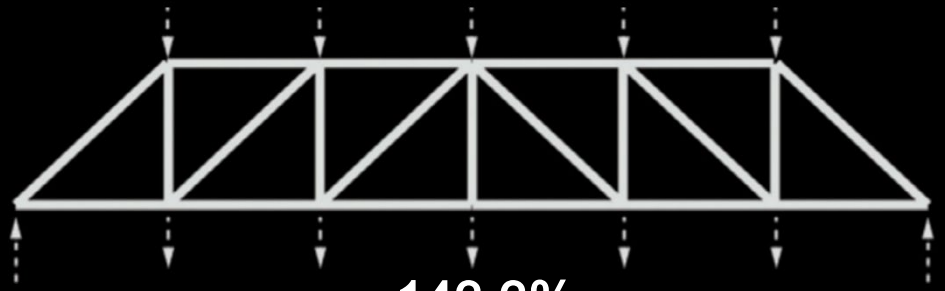
105.3%



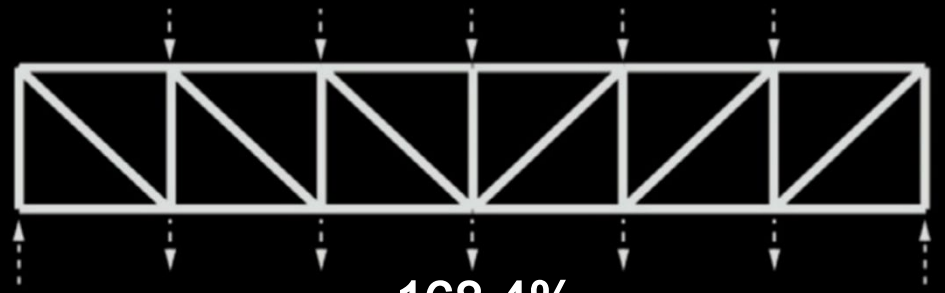
124.7%



129.2%



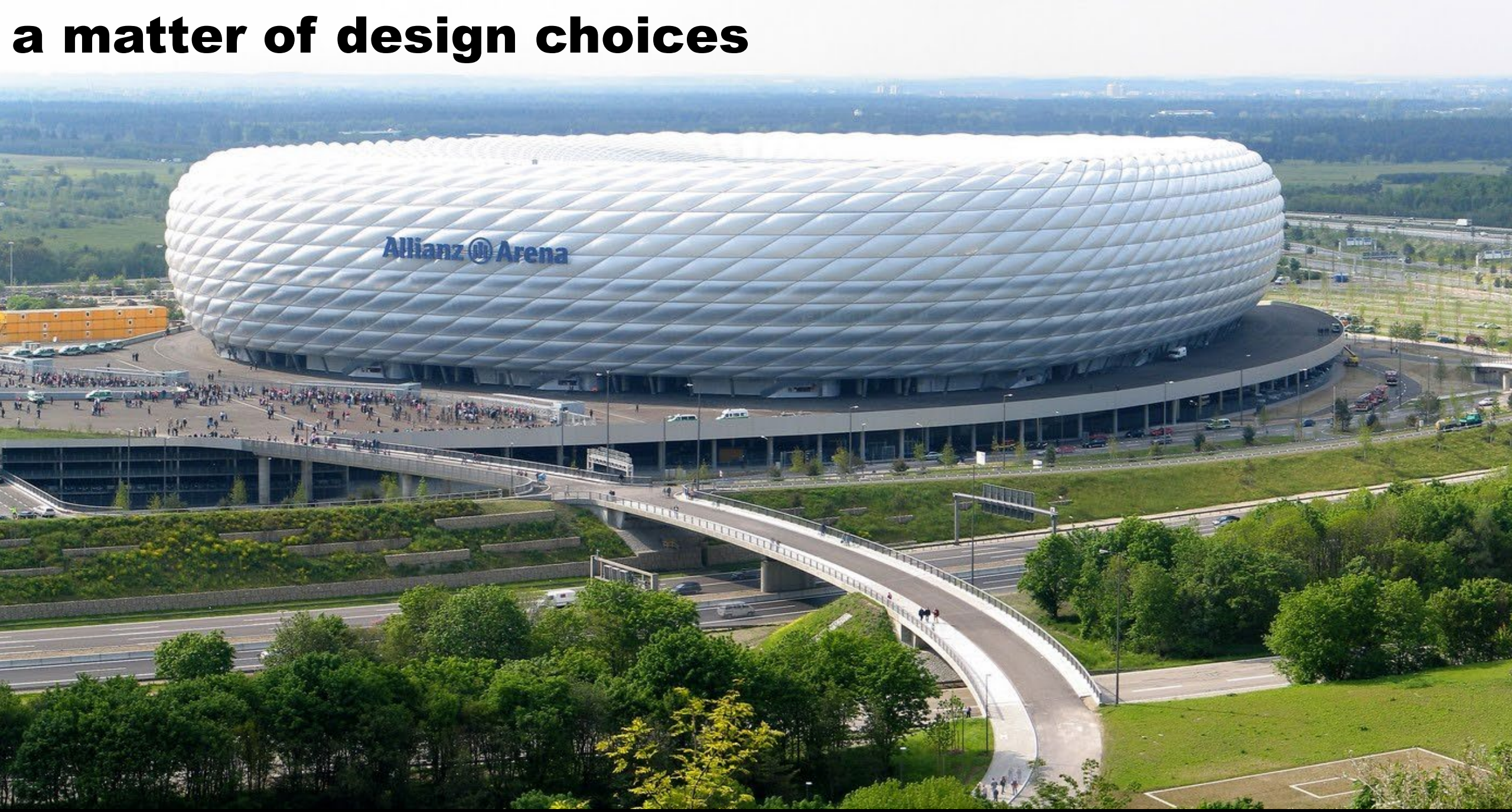
143.3%



168.4%

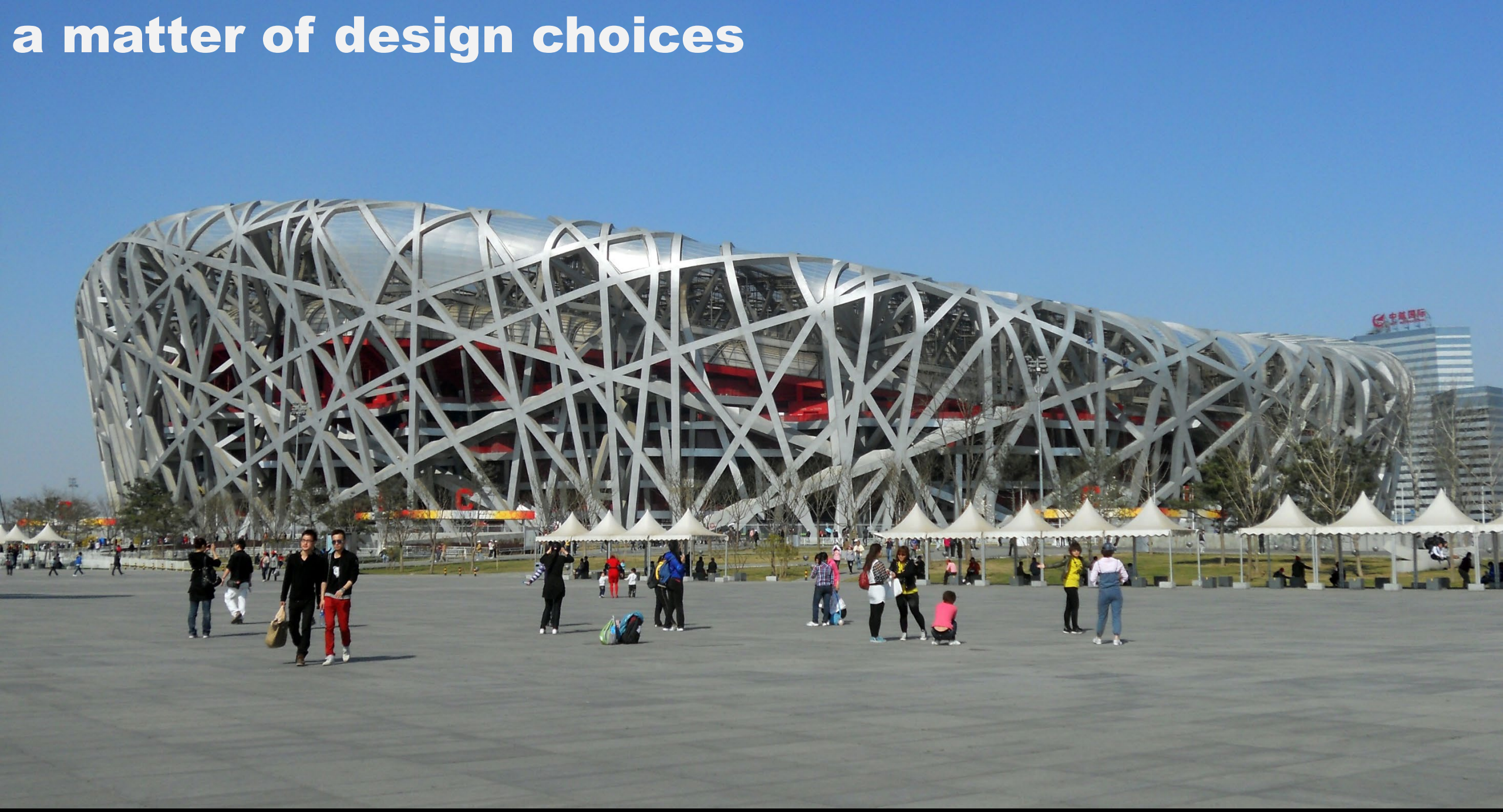
Baker et al. 2016 · Structural innovations: combining classic theories with new technolog

a matter of design choices



Allianz Arena 2005, Herzog & de Meuron, Arup

a matter of design choices



Beijing Olympics 2008, Herzog & de Meuron, ARUP

a matter of design choices

London Olympics Stadium 2012, Populous, Buro Happold

POLL: which stadia has the lowest embodied carbon per seat?

A

B

C

Join at
slido.com
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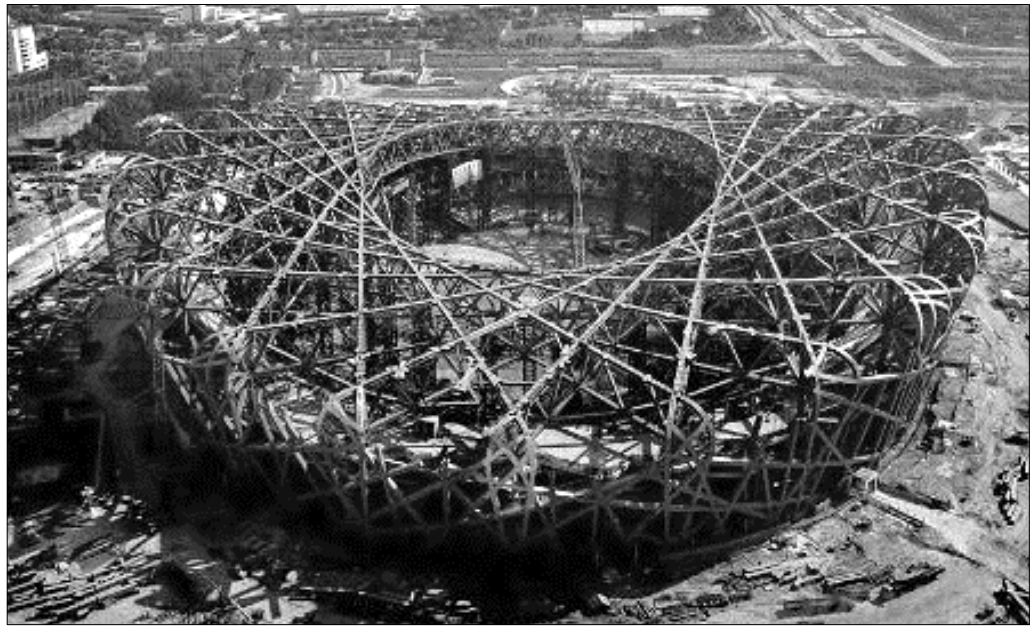
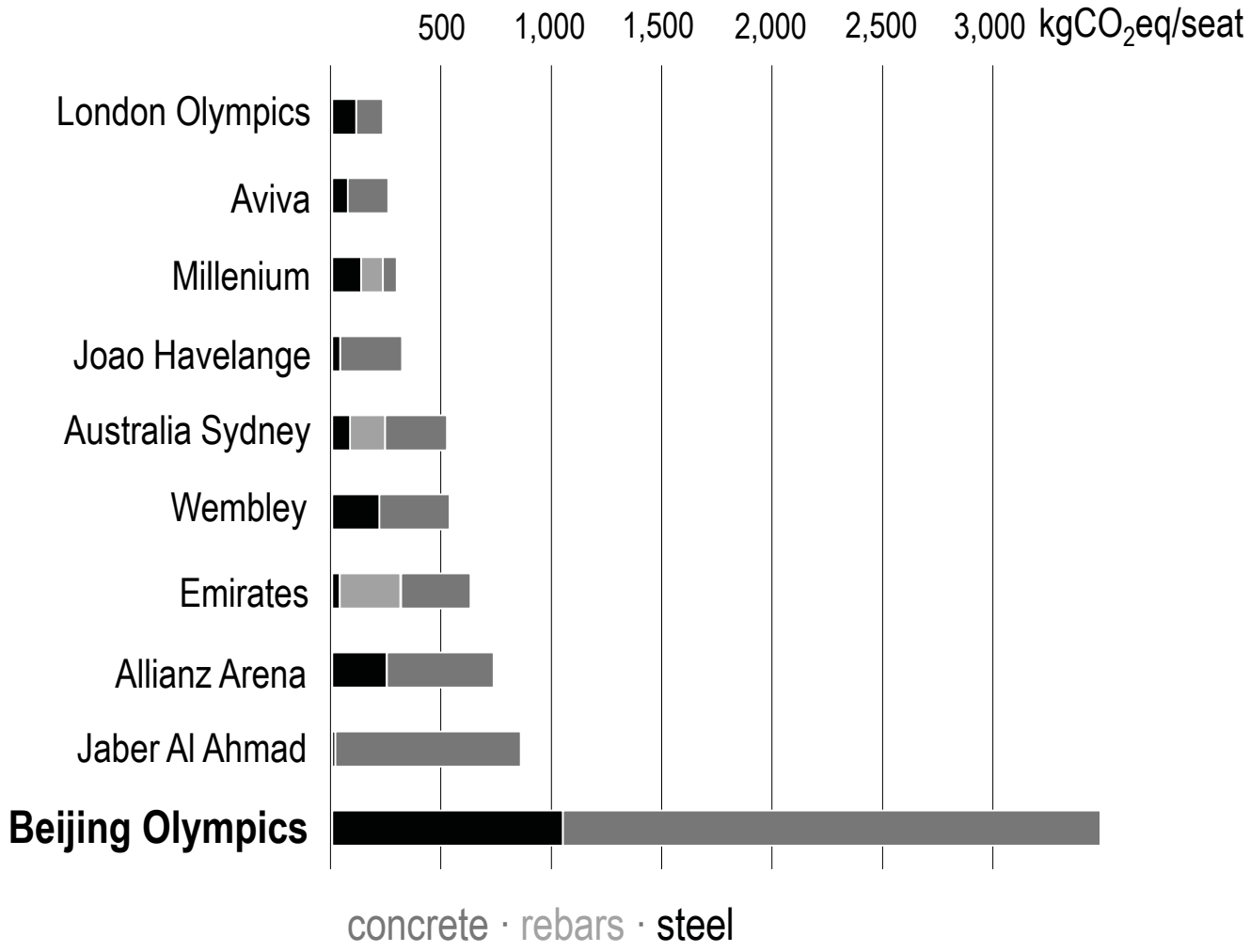
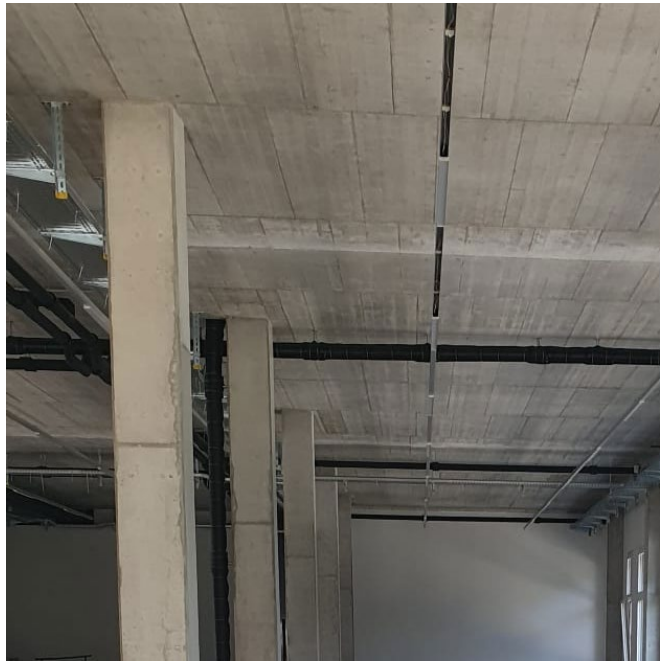
embodied carbon per seat





De Wolf et al. · Comparing material quantities and embodied carbon in

typologies of concrete slabs

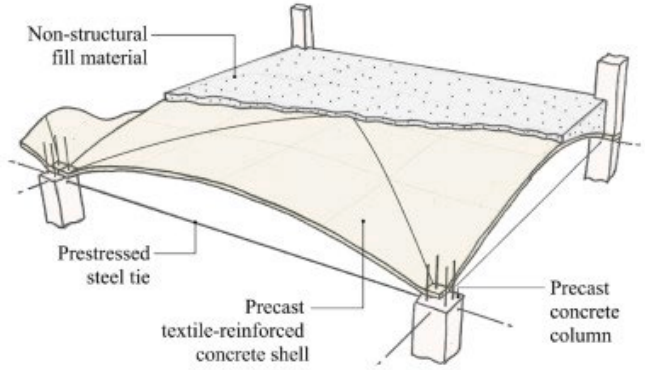


flat slab

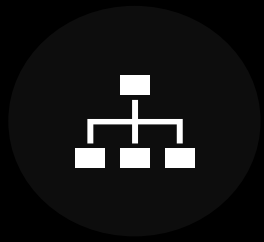
ribbed slab

thin shell floor

Up to -65% of CO_2-eq cradle-to-gate

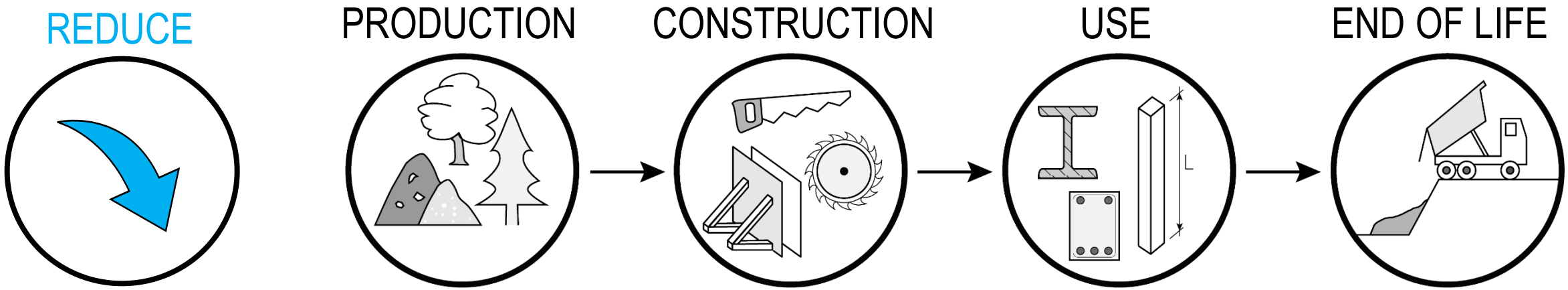


Jayasinghe et al. 2022, Comparing different strategies of minimising embodied carbon in concrete floors. Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2022.131177

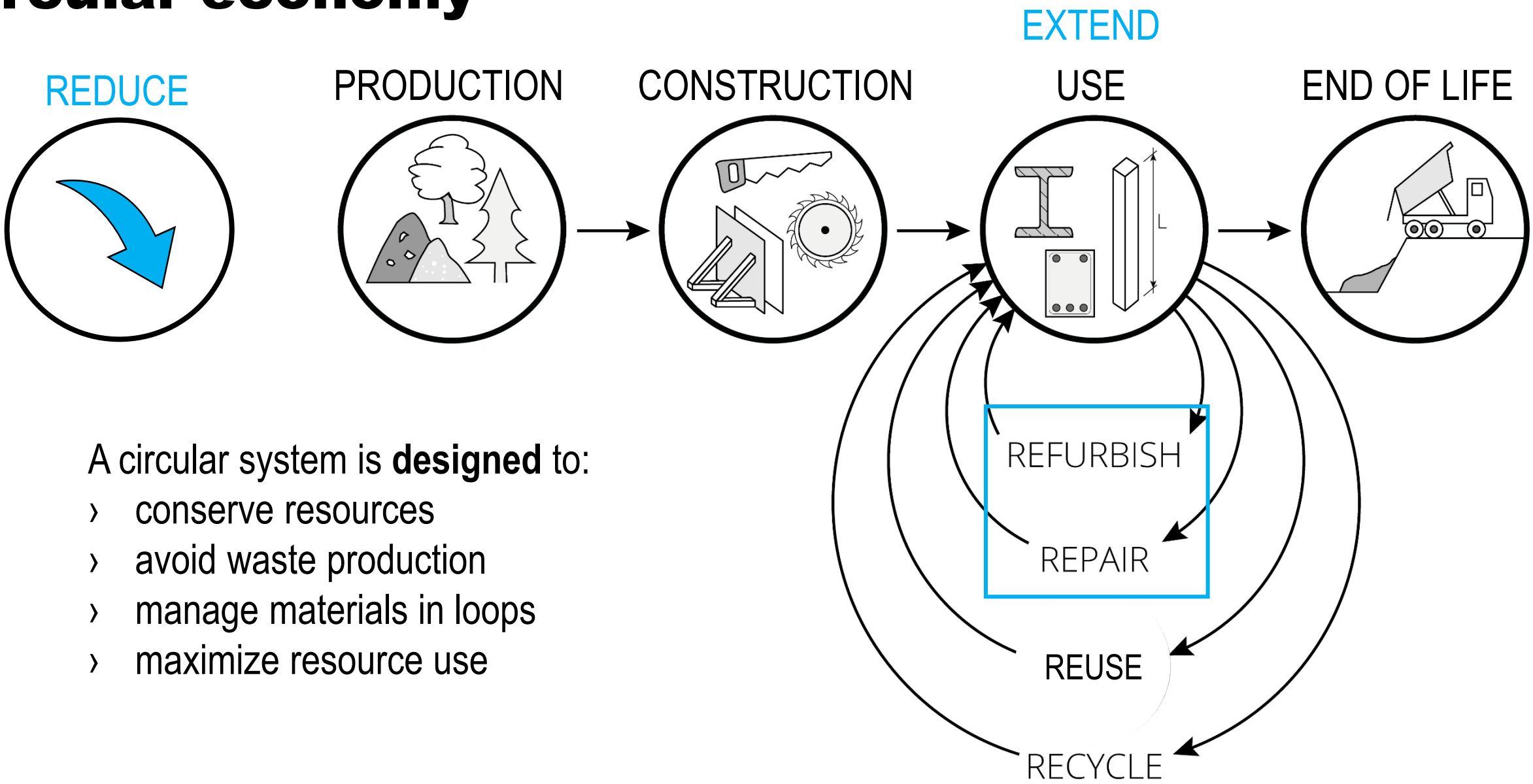


LIFESPAN

linear to circular economy



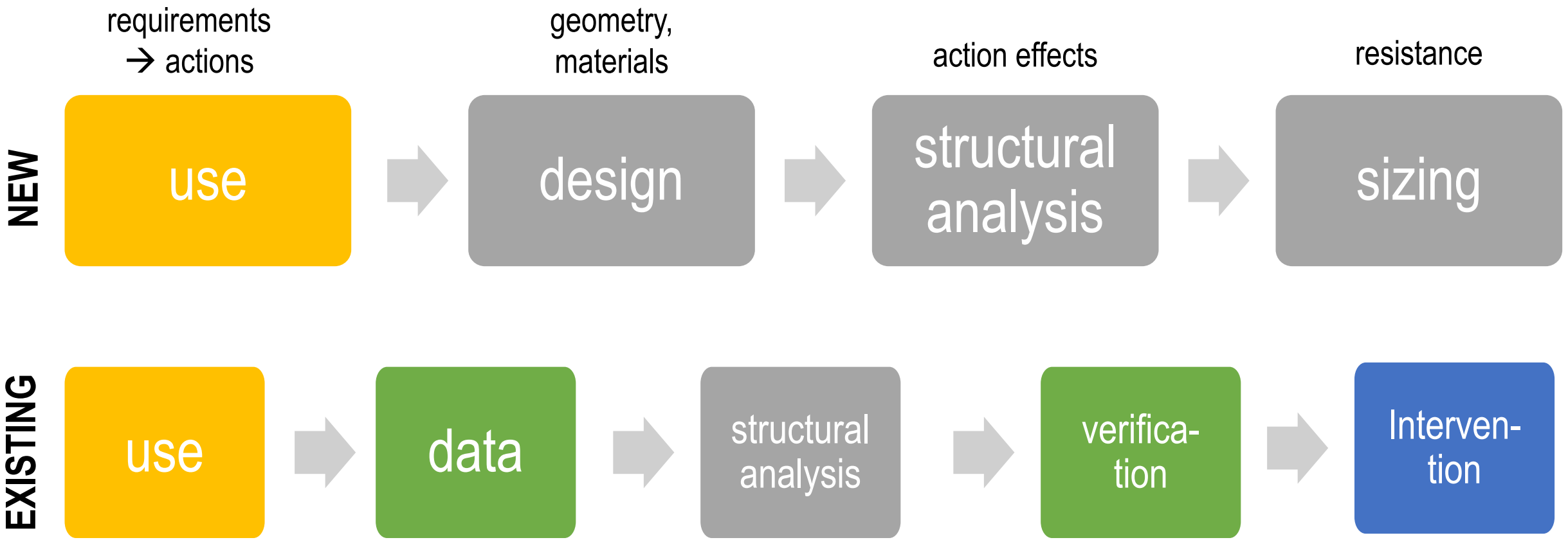
circular economy



A circular system is **designed** to:

- conserve resources
- avoid waste production
- manage materials in loops
- maximize resource use

verification process



verification of existing structures

Assess existing structures to plan interventions:

1. collect existing data
2. identify load-bearing system
3. survey the current state
4. update geometry, material properties and actions
5. verify structural safety
6. establish remaining service life
7. recommend interventions

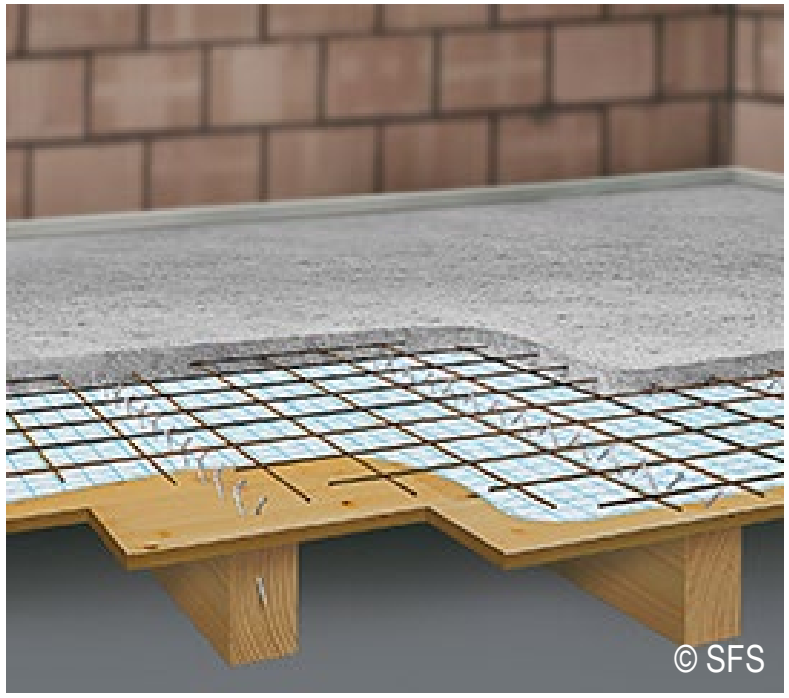
strengthening of structures

definition : intervention designed to improve the ultimate strength and serviceability of a load-bearing structure.

UHPFRC layer

carbon lamella

concrete overlay



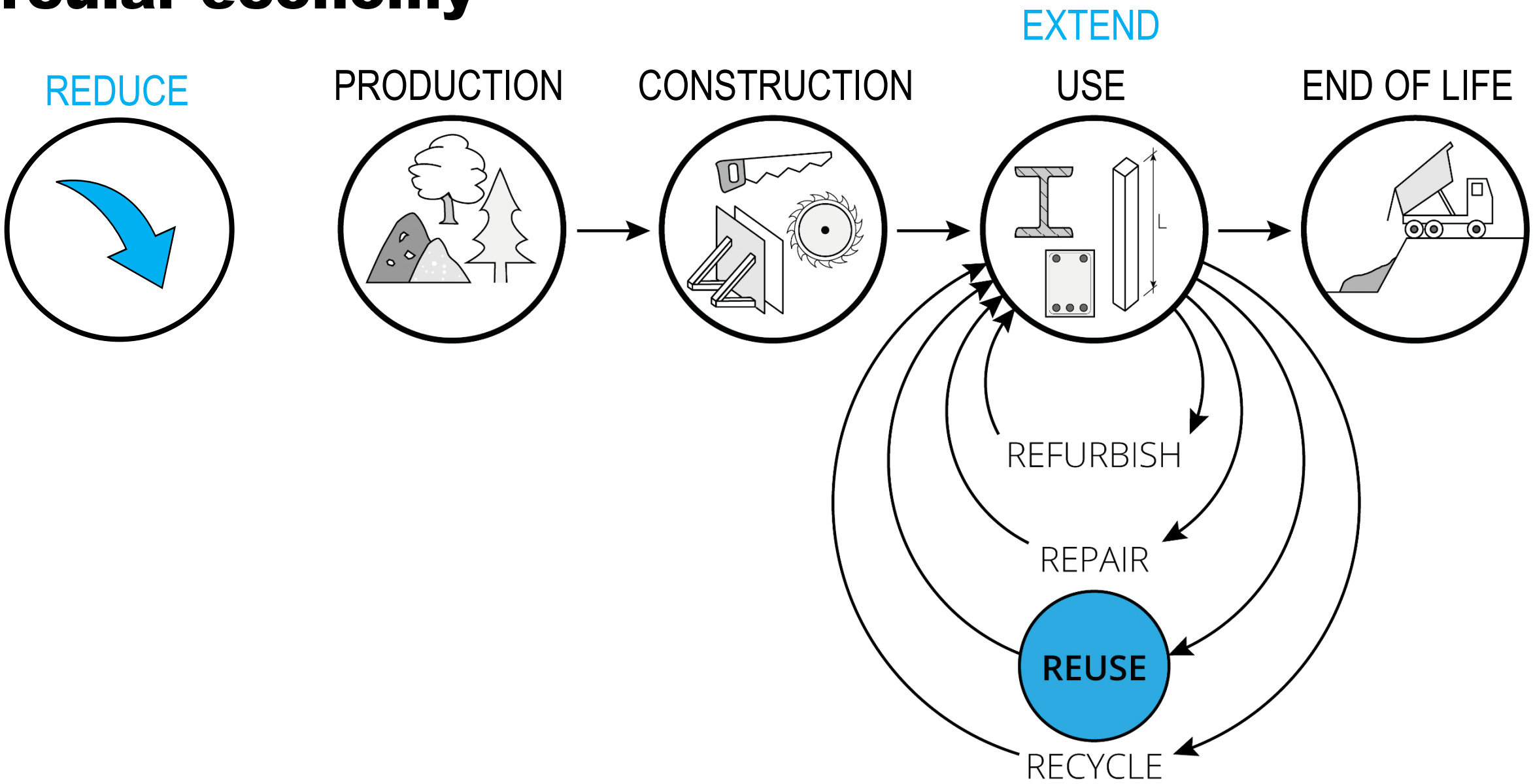
Any transformation has an environmental cost, generally lower than the cost of demolition/reconstruction!

maintain and transform structures

Renovation, extension and elevation of a rental building - 9 avenue Wendt, Genève

Owner : Vaudoise Vie, Compagnie d'Assurance SA
Contractor : HRS Real Estate SA
Architect : Clavien & Associés Sàrl
Civil engineer : Nicolas Fehlmann Ingénieurs Conseils SA
Execution : 2023 - 2024

circular economy



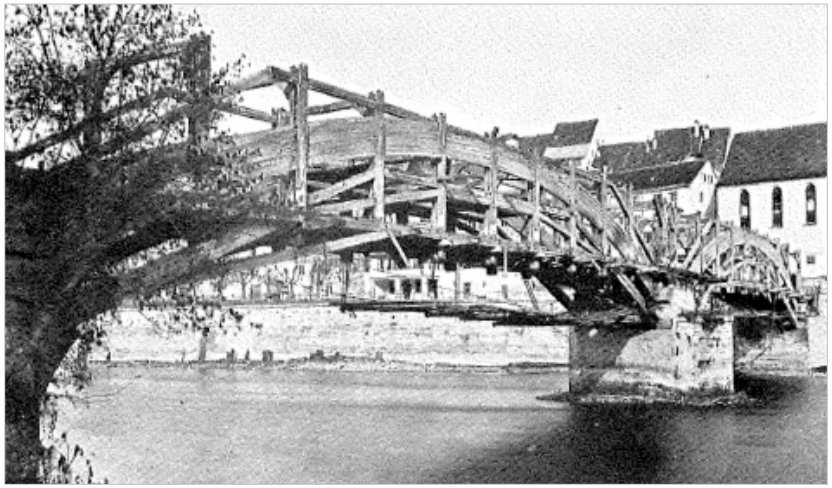
commonplace

Genève, 1898 © Boissonnas, Bibliothèque de Genève

reuse of construction components

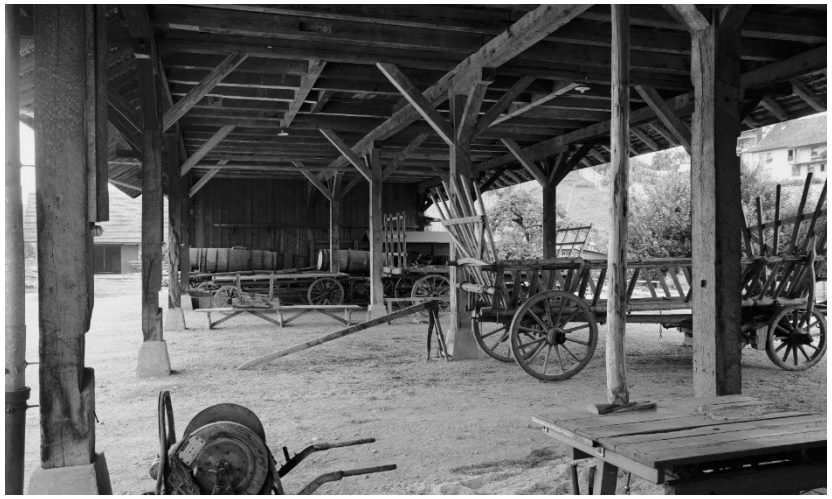
1810

1919



Eglisau, CH

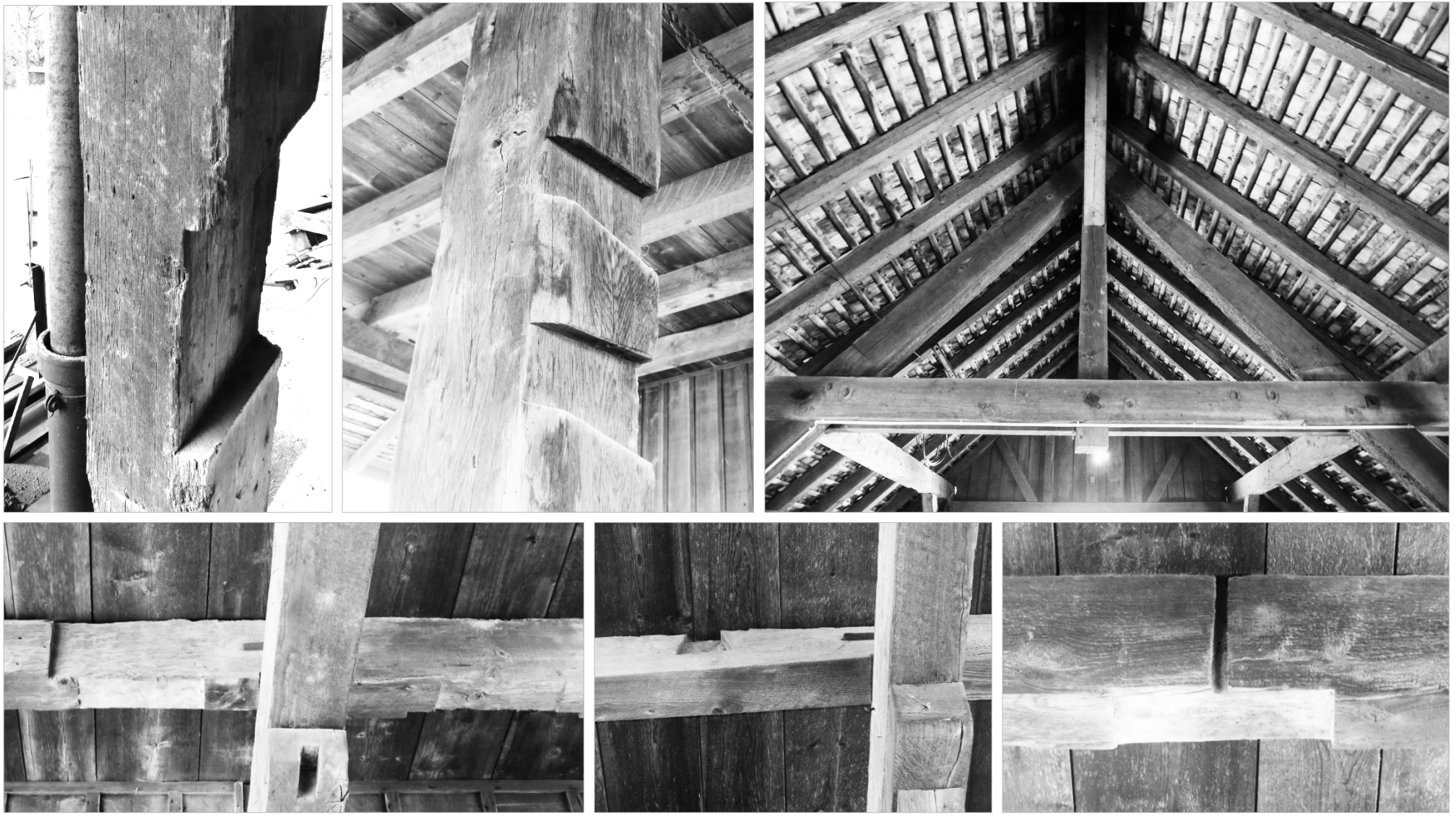
Rheinau, CH



1920

2019

C.Fivet, J.Brütting · Nothing is lost, nothing is created, everything is reused - The new structural design assignment for the circular economy · 2019



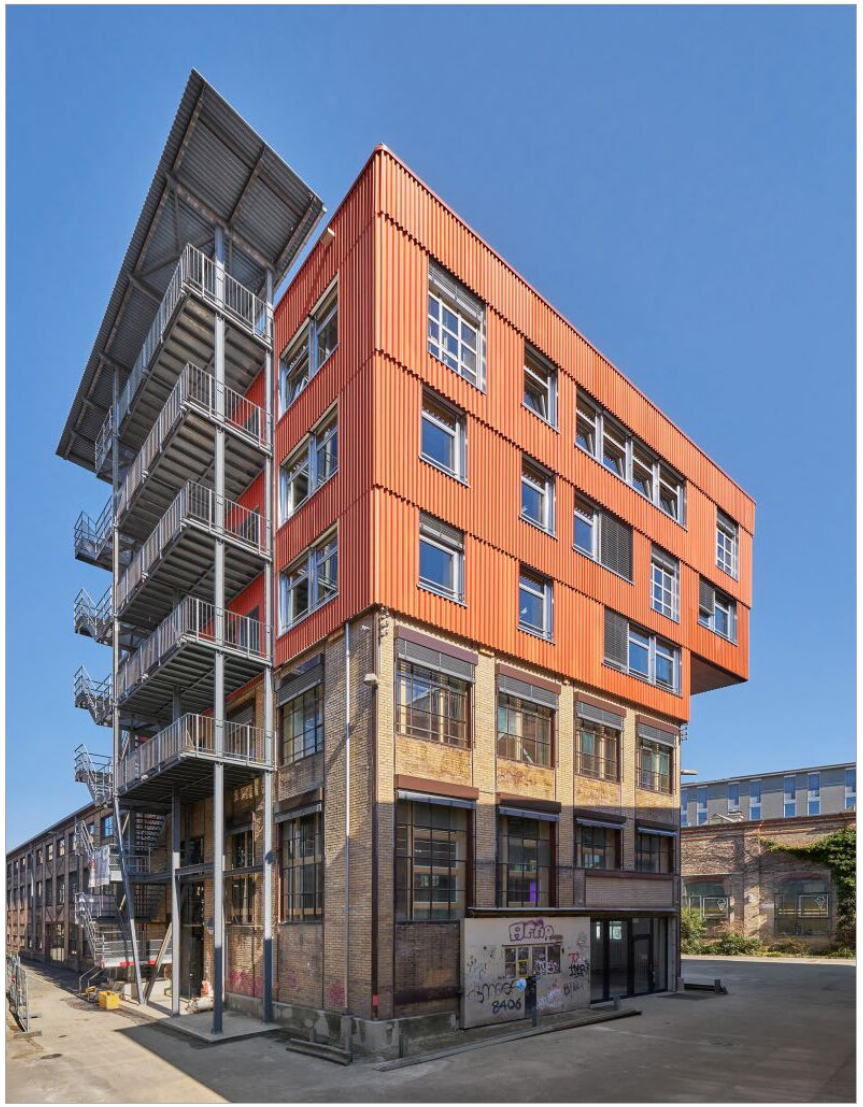
C.Fivet, J.Brütting · Nothing is lost, nothing is created, everything is reused - The new structural design assignment for the circular economy · 2019

recent example

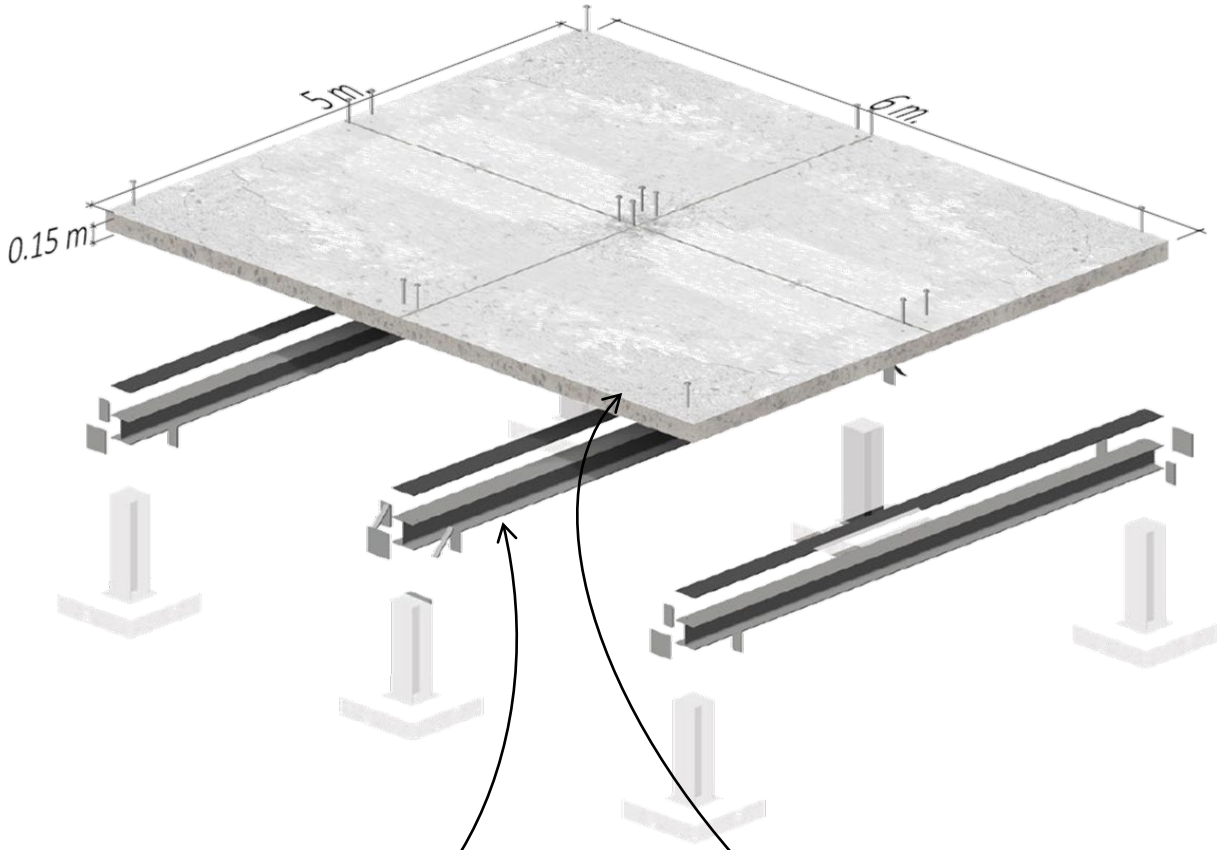
existing building

supply

rehabilitation and reuse



reclaimed floor system



reclaimed steel beams

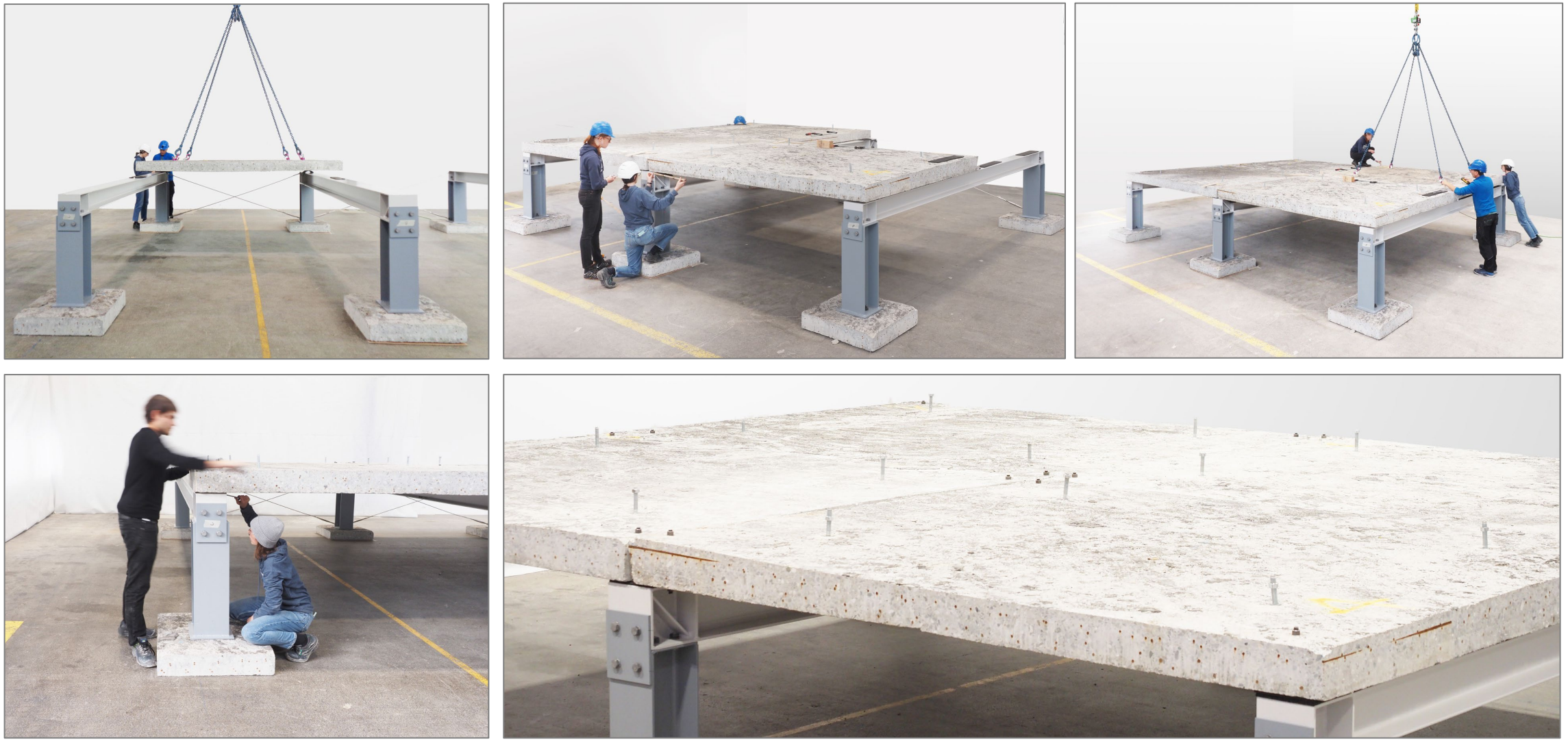
saw-cut reinforced concrete slabs

Küpfer et al. 2025· Design, construction and assessment of FLO:RE – the prototype of a low-carbon building floor made of reused concrete elements and steel profiles. Architecture, Structures and Construction, https://doi.org/10.1007/s44150-025-00138-2

roof slab

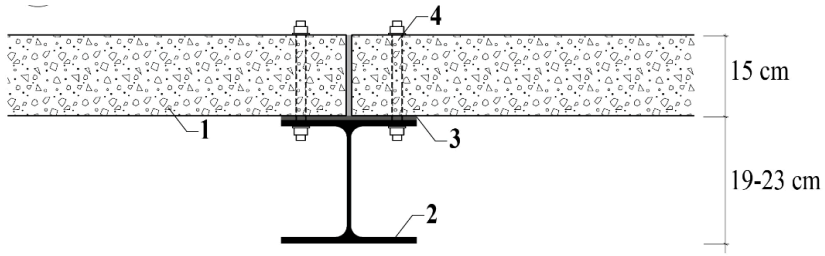
steel frame

construction process

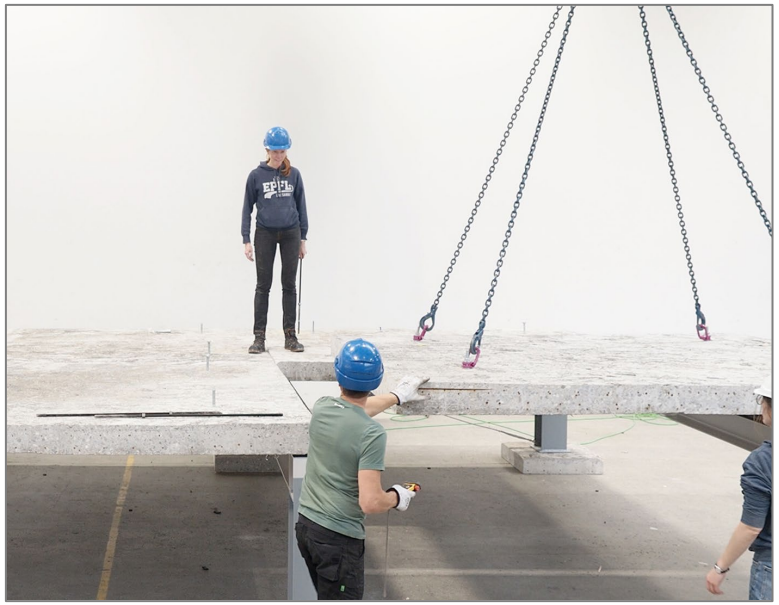


Küpfer et al. 2025· Design, construction and assessment of FLO:RE – the prototype of a low-carbon building floor made of reused concrete elements and steel profiles. Architecture, Structures and Construction, https://doi.org/10.1007/s44150-025-00138-2

dry connections

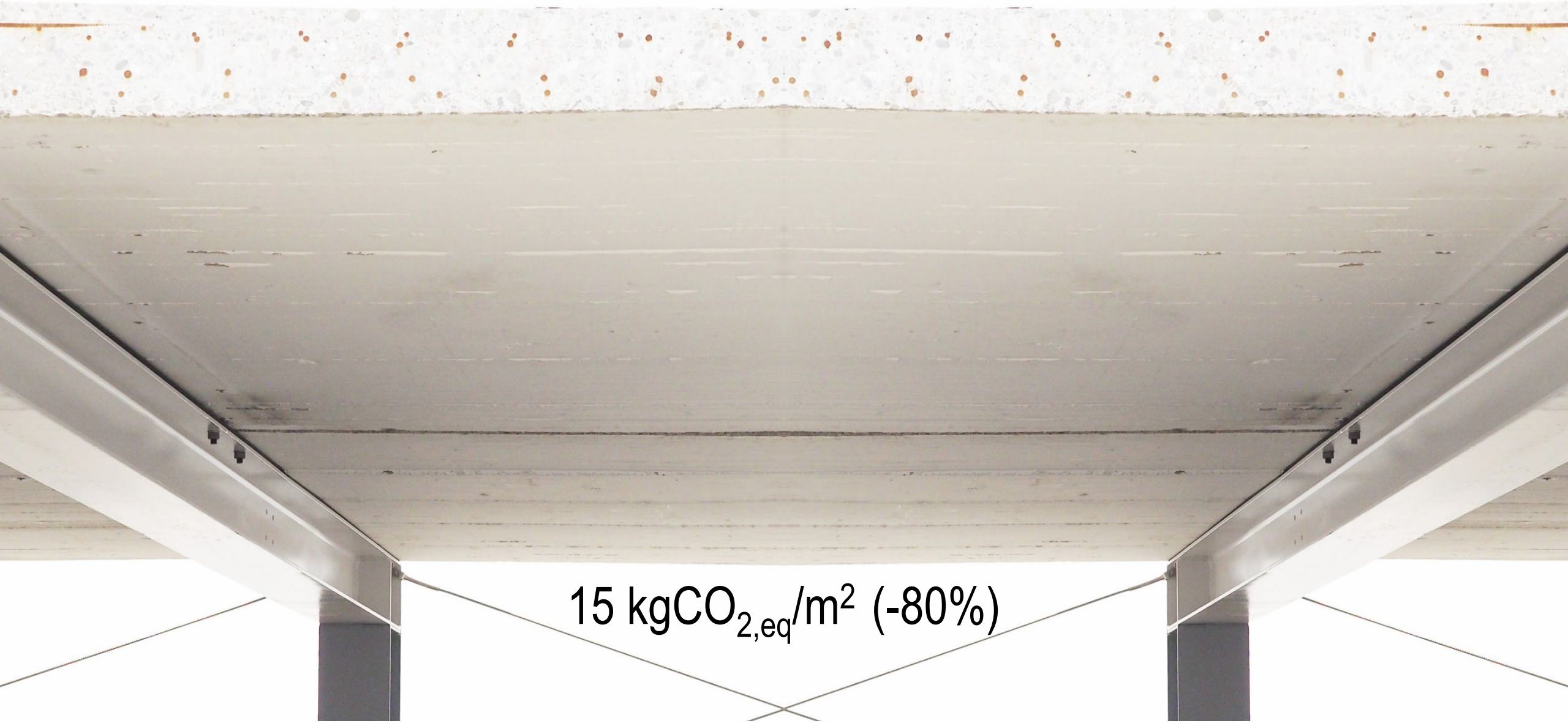


1 Reused 15-cm saw-cut reinforced-concrete slab (3 m x 2.5m)
2 Reused steel profile (HEA 200 and HEA 240) (5 m)
3 8-mm recycled rubber
4 ø16-mm prestressed threaded rod



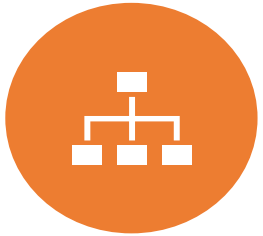
Küpfer et al. 2025· Design, construction and assessment of FLO:RE – the prototype of a low-carbon building floor made of reused concrete elements and steel profiles. Architecture, Structures and Construction, https://doi.org/10.1007/s44150-025-00138-2

ultra-low carbon slab



session recap

BASICS OF STRUCTURAL DESIGN



IMPACTS OF STRUCTURES

MATERIALS

STRUCTURAL SYSTEMS

LIFESPAN