CIVIL-239
Engineering a sustainable built environment

Lecture 07

Embodied carbon of materials and structures

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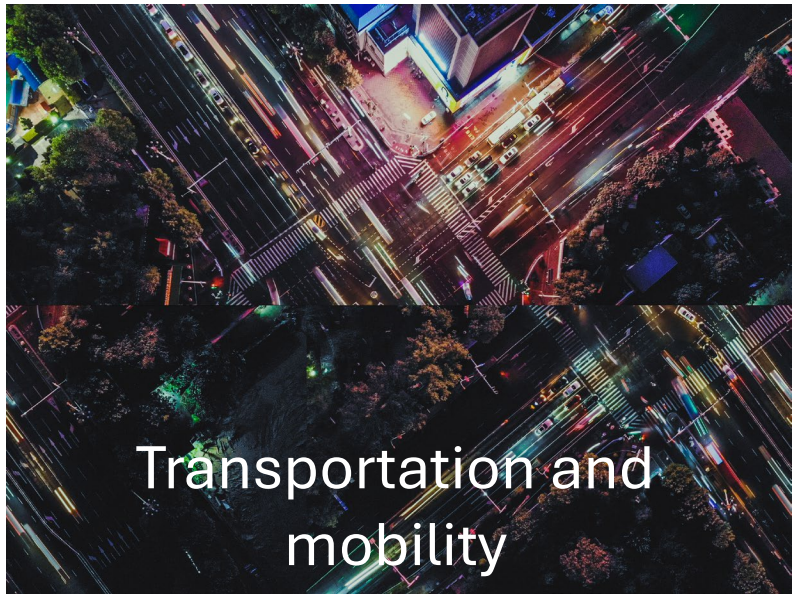
EPFL STRUCTURAL XPLORATION LAB

November 5th 2024

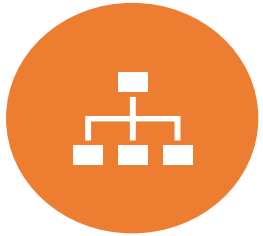
Housekeeping

- Assignments 4 and 5 pushed back one week (due to guest lecture schedule)
  - See updated course schedule
  - Assignment 4 – due 26 November
  - Assignment 5 – due 10 December
- Midterm grades to be released next week

Subdisciplines of civil engineering



session overview



LIFE PHASES OF STRUCTURES

BASICS OF STRUCTURAL DESIGN

MATERIALS

STRUCTURAL SYSTEMS

LIFESPAN

life phases of structures

what is a structure?

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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

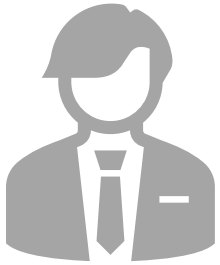
Leibstadt Nuclear Power Plant

geotechnical structures

Liaison Ouest, Plateforme 10, Lausanne
retaining wall

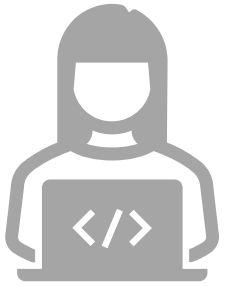
Elysée/mudac, Plateforme 10, Lausanne
excavation supports

roles



Owner

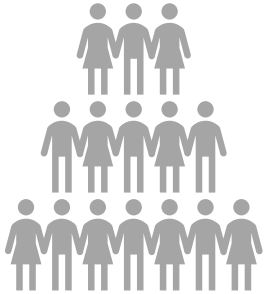
(maître d'ouvrage)



Designer and planner
(architectes and engineers)

Builders

(contractors)

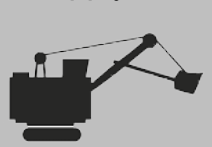


Users

LIFE PHASES

PRODUCTION

supply



manufacturing

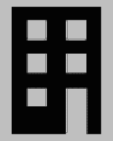
CONSTRUCTION

transport

construction

USE

maintenance/refurbishment

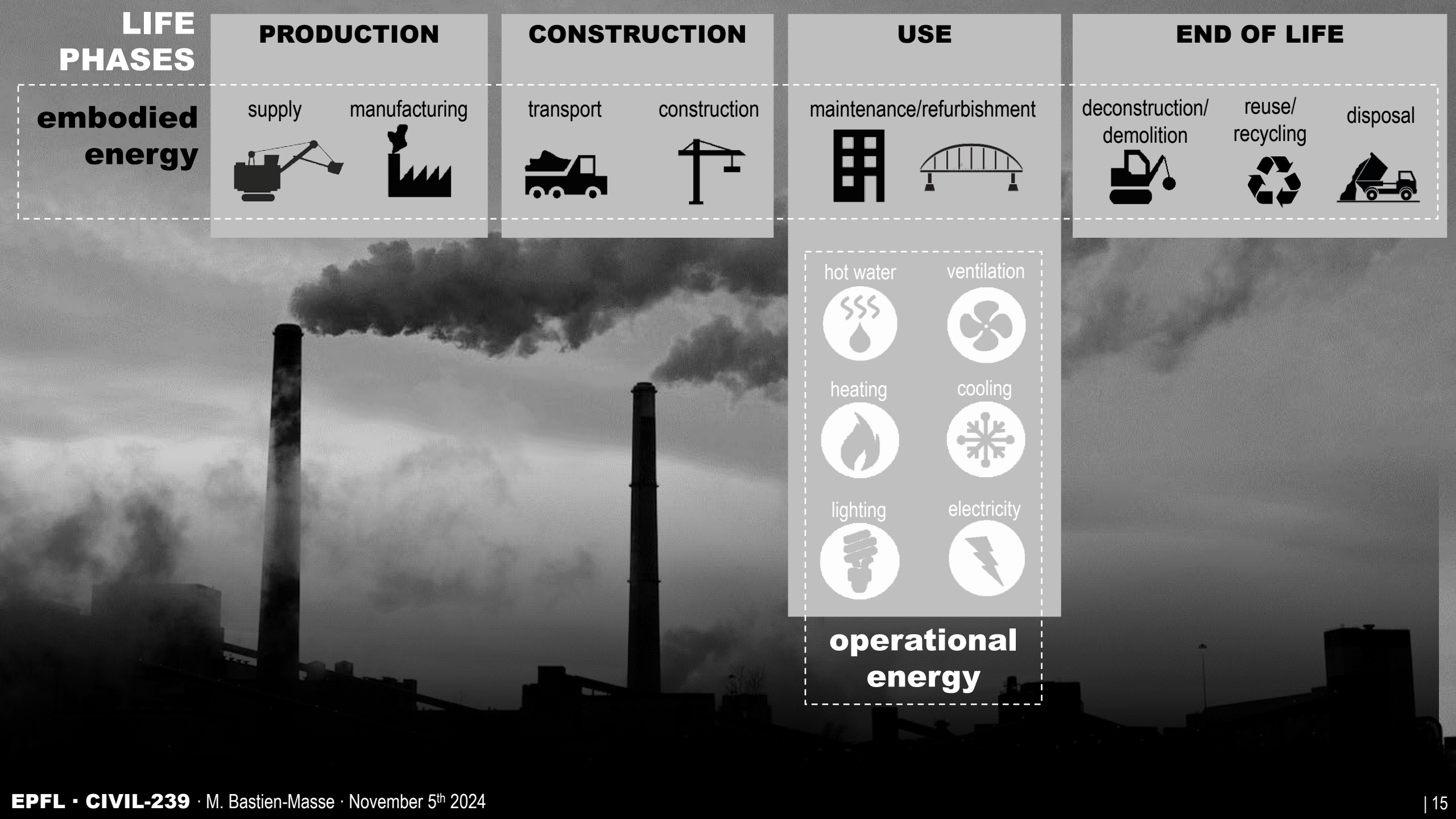


END OF LIFE

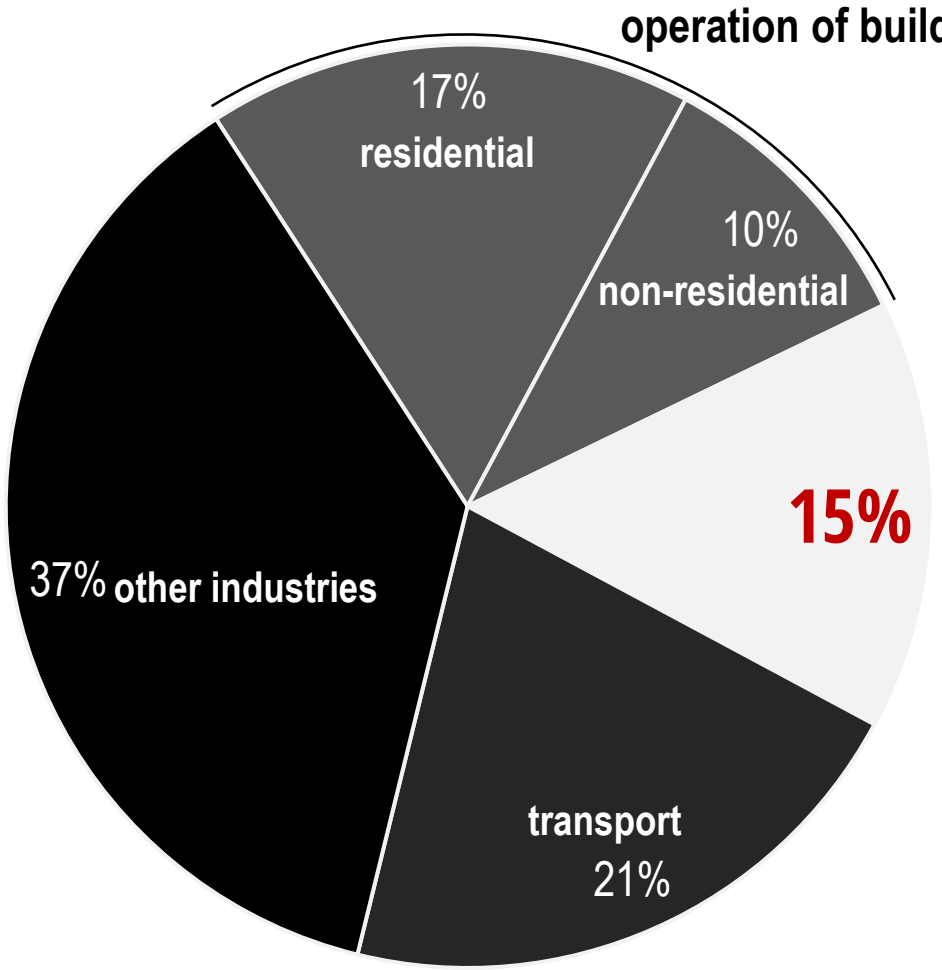
deconstruction/ demolition

reuse/ recycling

disposal

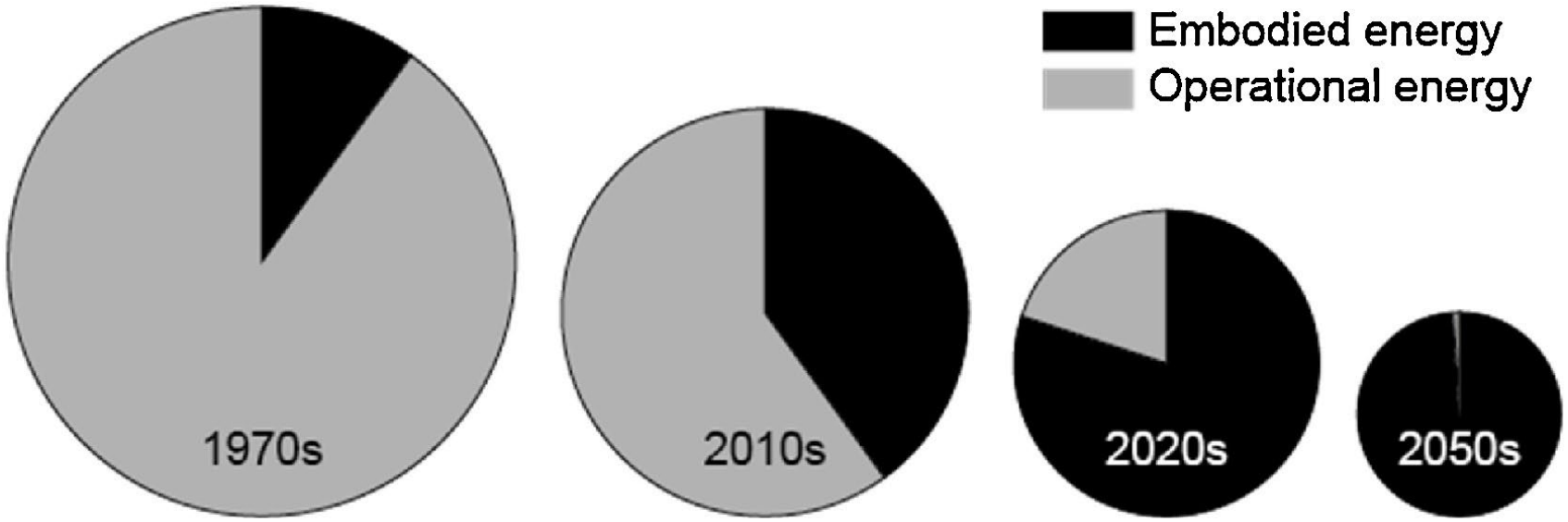

LIFE PHASES
PRODUCTION
CONSTRUCTION
USE
END OF LIFE
embodied energy
supply
manufacturing
transport
construction
maintenance/refurbishment
deconstruction/ demolition
reuse/ recycling
disposal
hot water
ventilation
heating
cooling
lighting
electricity
operational energy

anthropogenic global greenhouse gas emissions



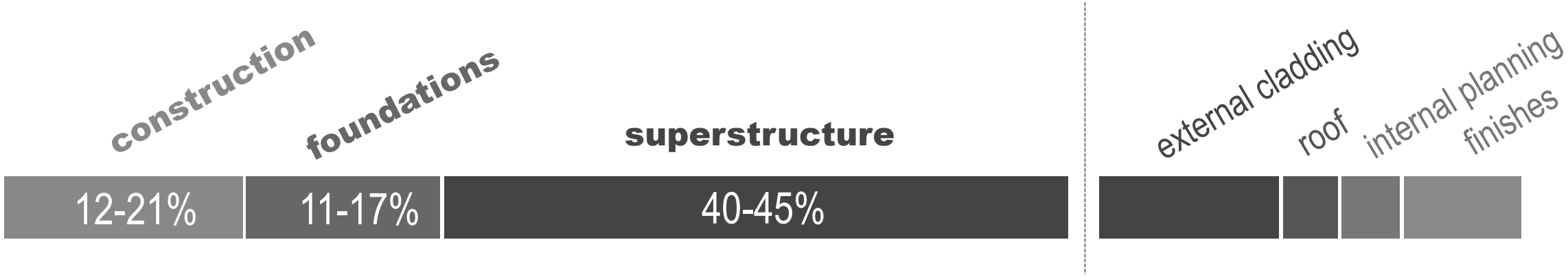
Global Status Report for Buildings and Construction · p.42 · GABC-IEA-UN · 2022

greenhouse gas emissions due to buildings



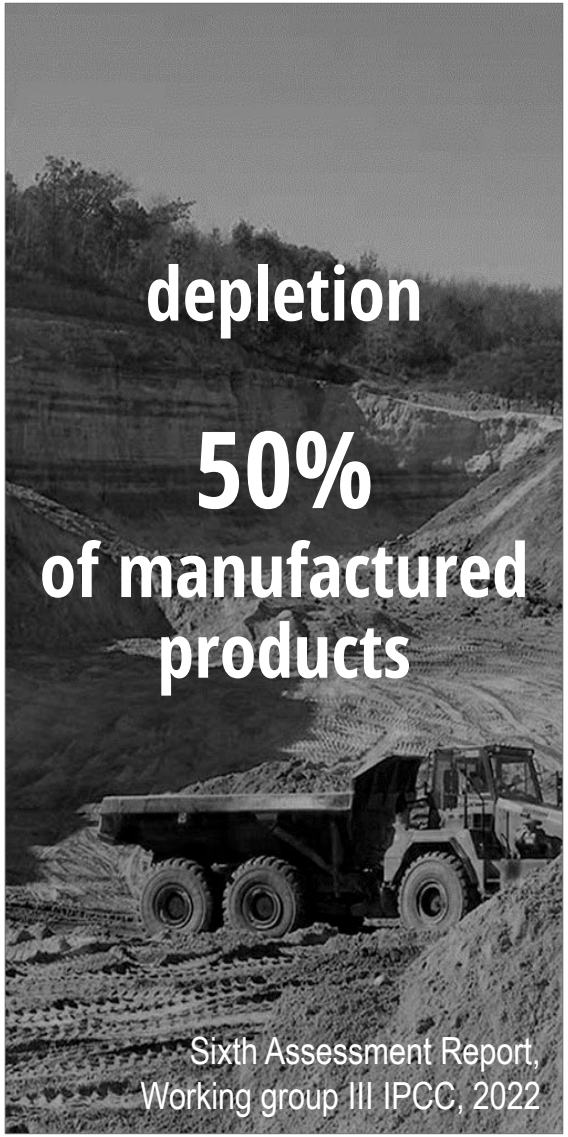
Orr et al. 2019. Minimising energy in construction: Practitioners' views on material efficiency, Resources, Conservation and Recycling, https://doi.org/10.1016/j.resconrec.2018.09.015.

greenhouse gas emissions of load-bearing structures

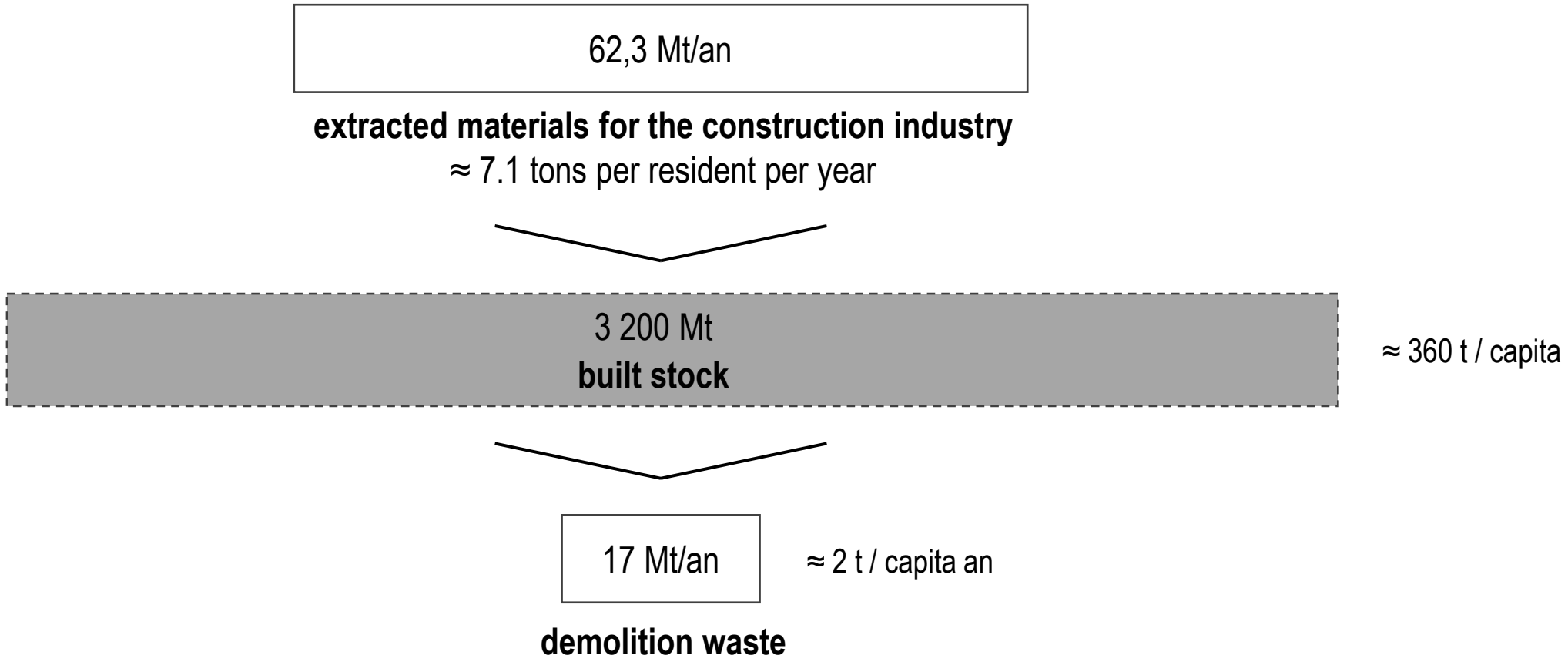


Embodied CO2 of structural frames · S.Kaethner & J.Burridge · The Structural Engineer, London, United Kingdom, pages 33-40 · 2012

construction sector



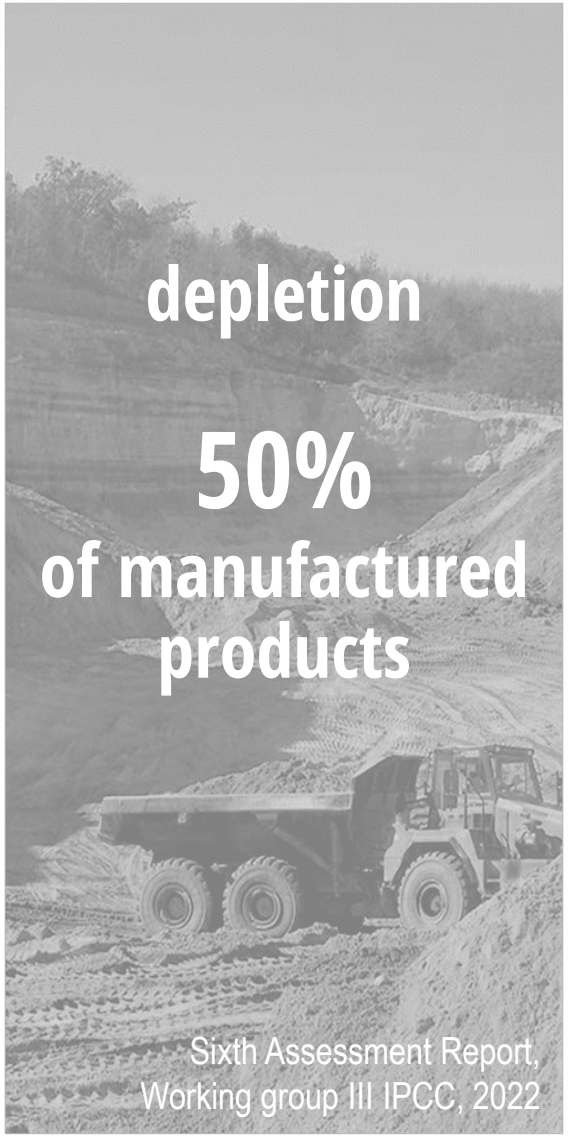
material extraction in Switzerland



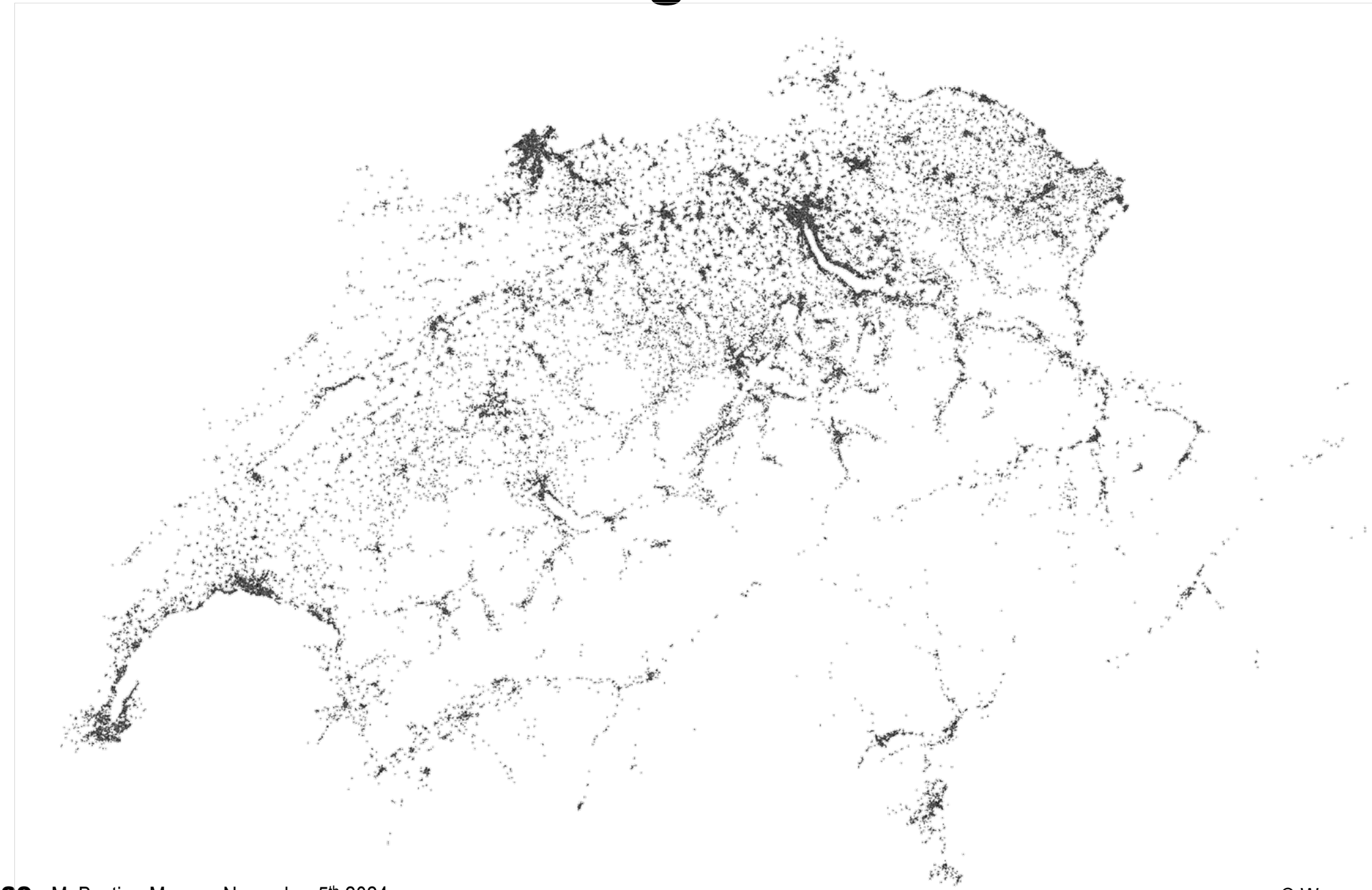
1 Mt (million tons) = 1 000 000 tons

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

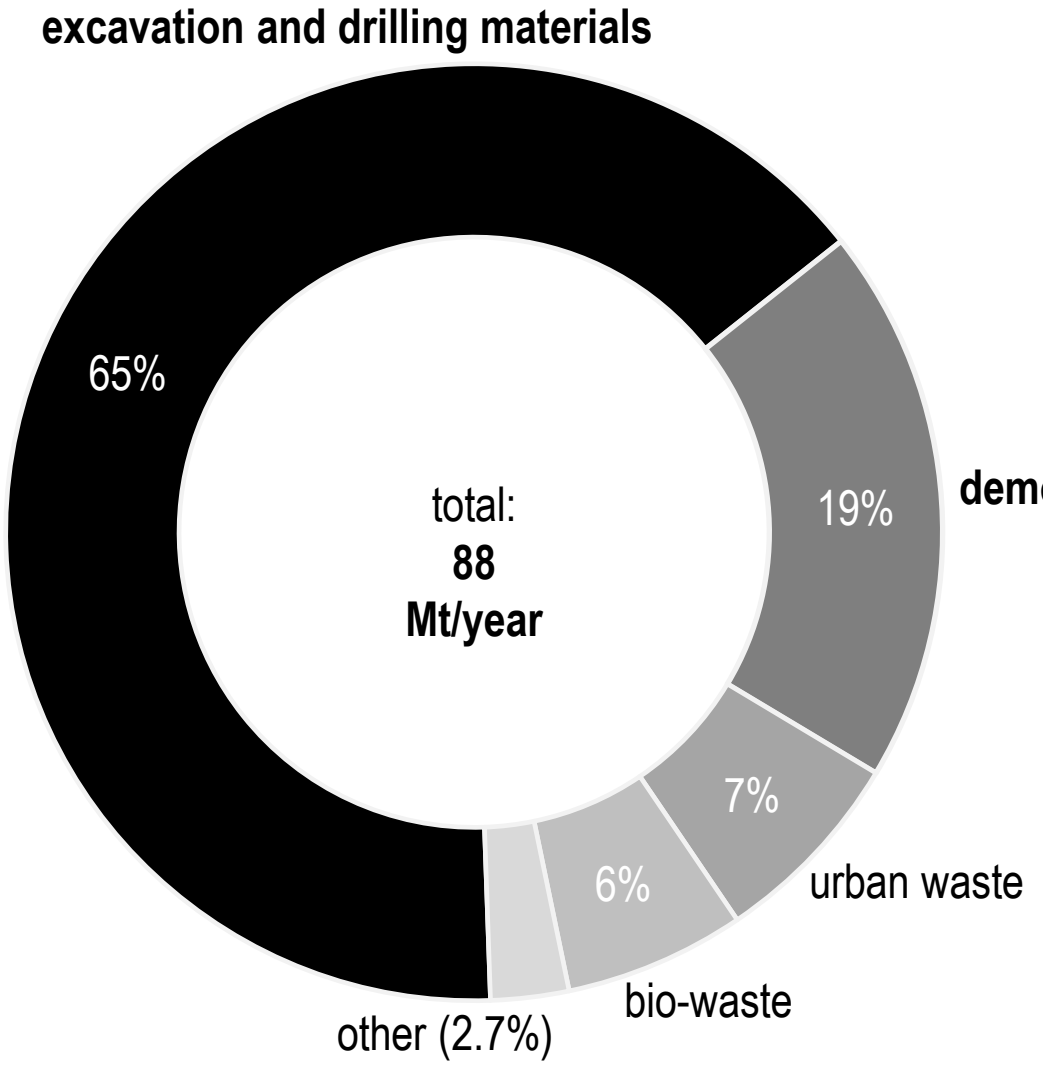
construction sector



70’000 demolished building between 2000 et 2022



déchets générés en Suisse



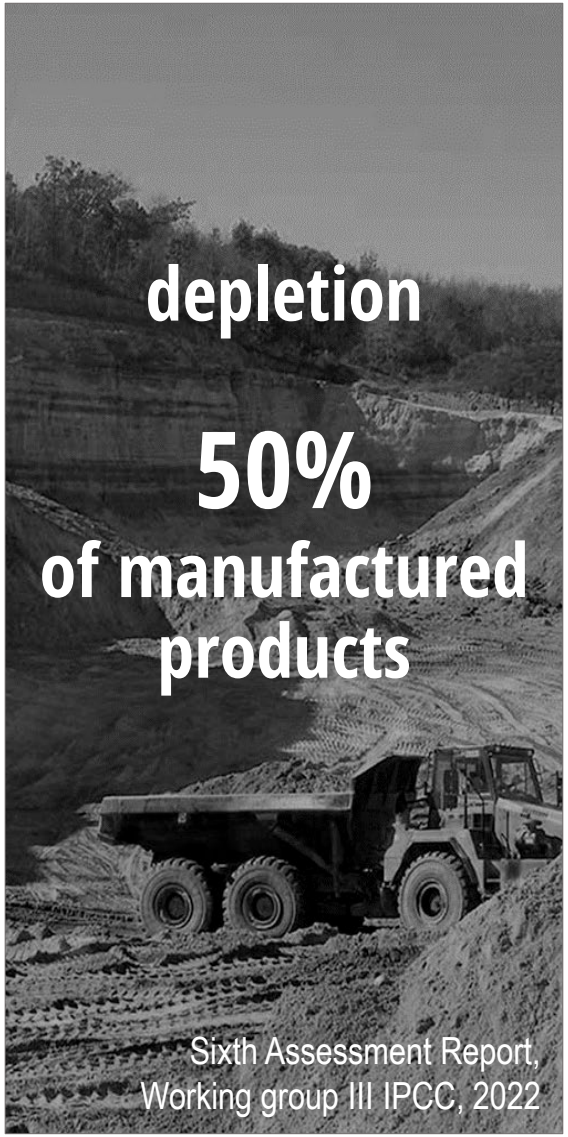
demolition waste

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

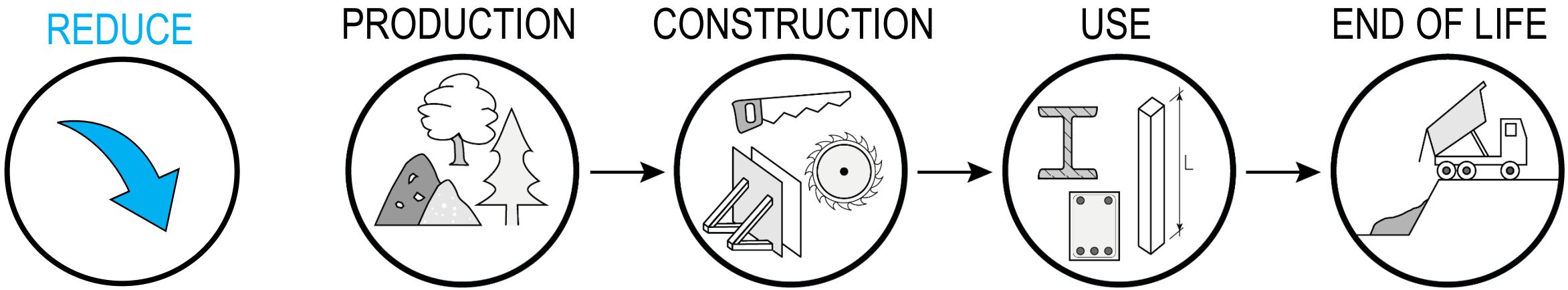
1 Mt (million tons) = 1 000 000 tons

OFEV (2022) Déchets et matières premières en bref (données de 2017)

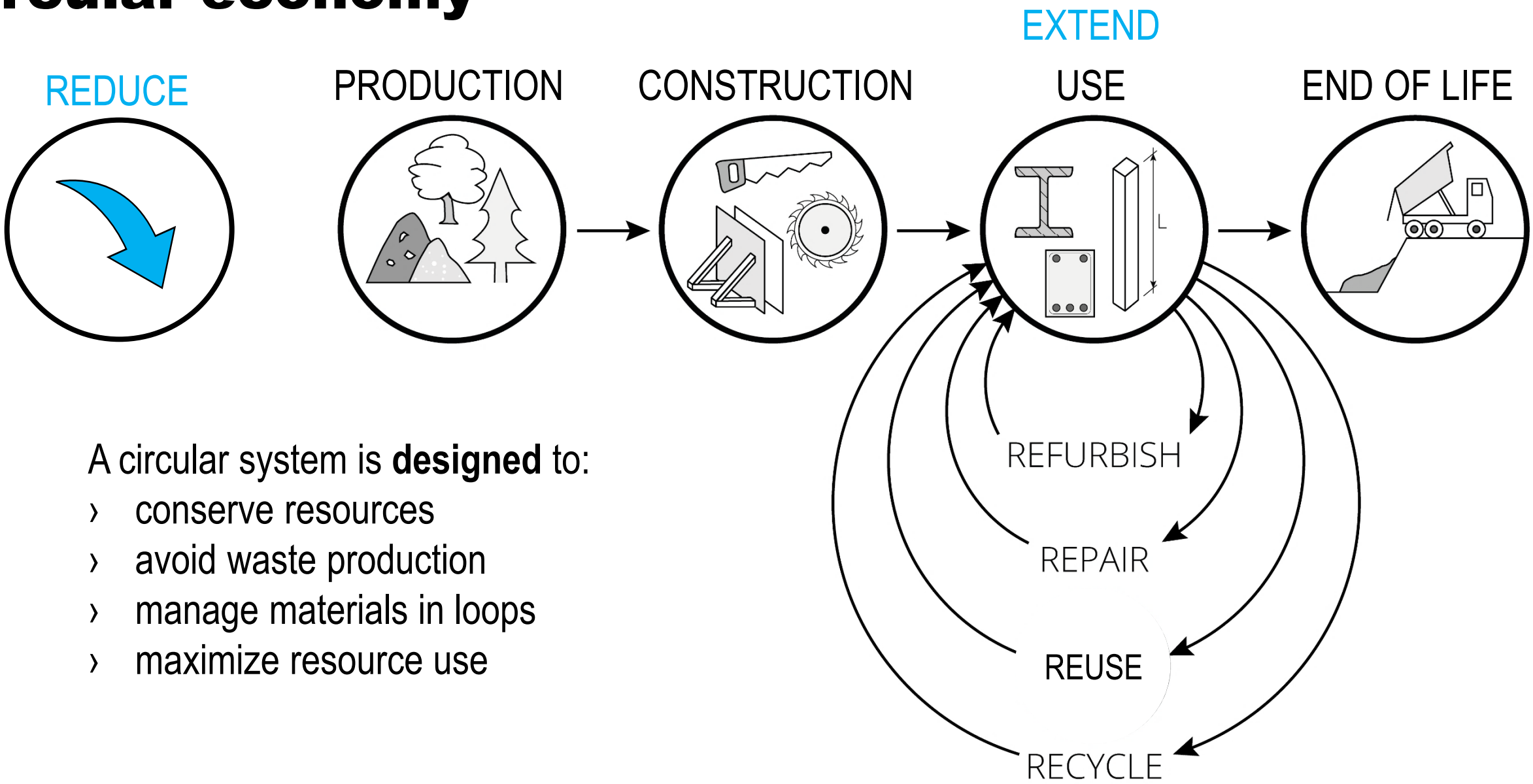
construction sector



linear to circular economy



circular economy

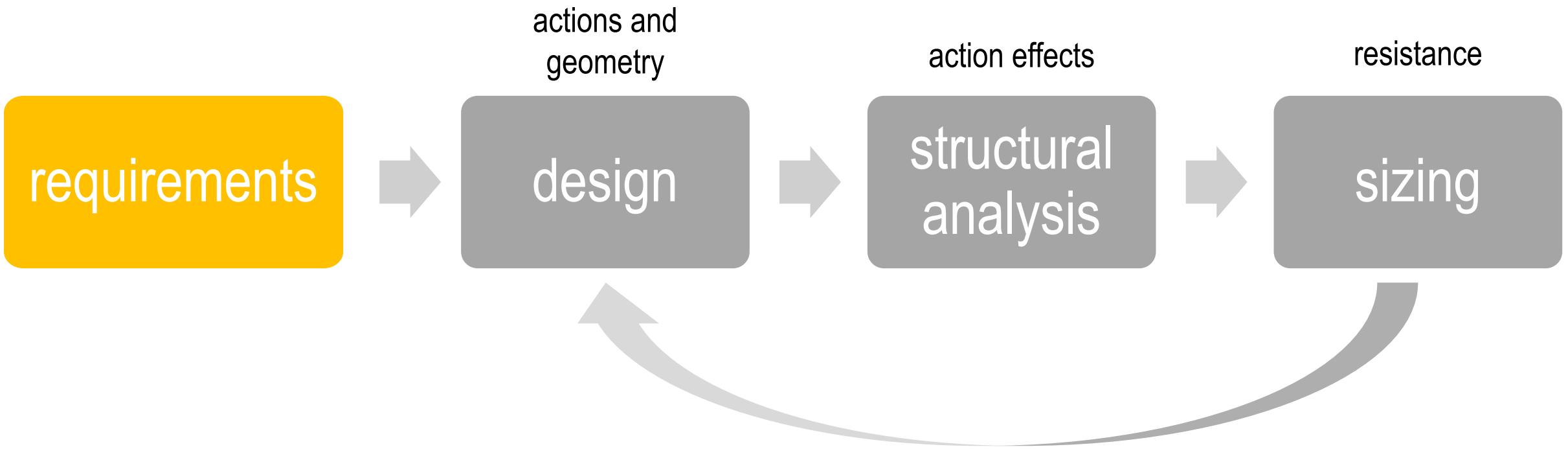


A circular system is **designed** to:

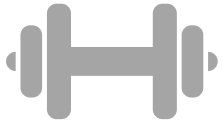
- conserve resources
- avoid waste production
- manage materials in loops
- maximize resource use

basics of structural design

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

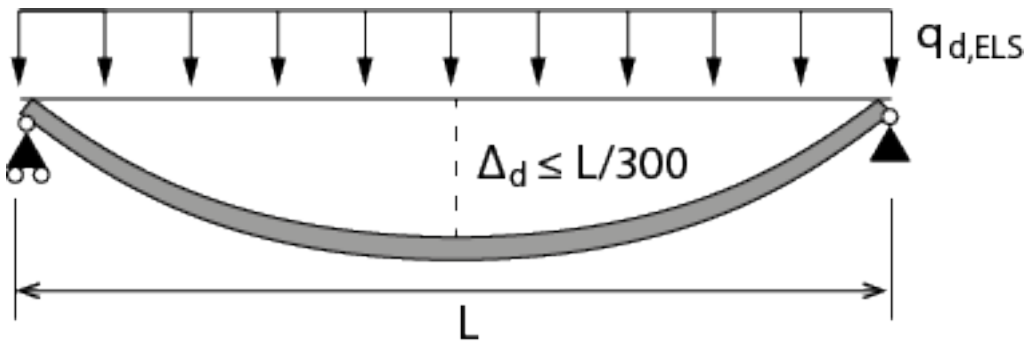
limit states

Serviceability Limit State (SLS)

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

Deformations due to action ≤ Allowable deformations

Example: Verification of deflections ≤Δ

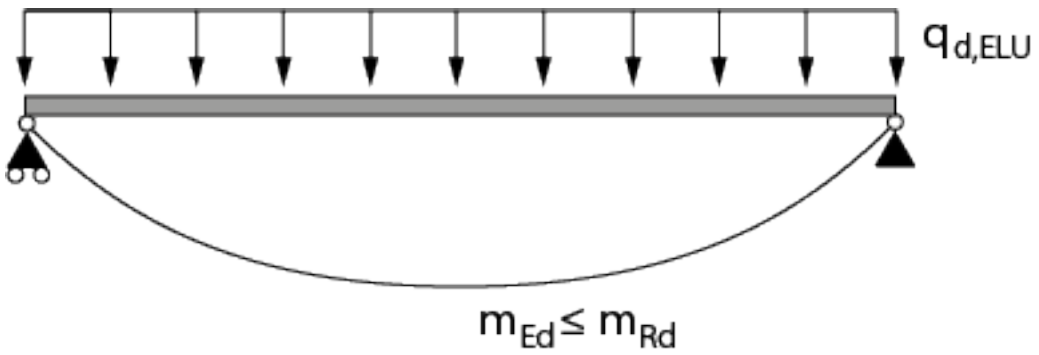


Ultimate Limit State (ULS)

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

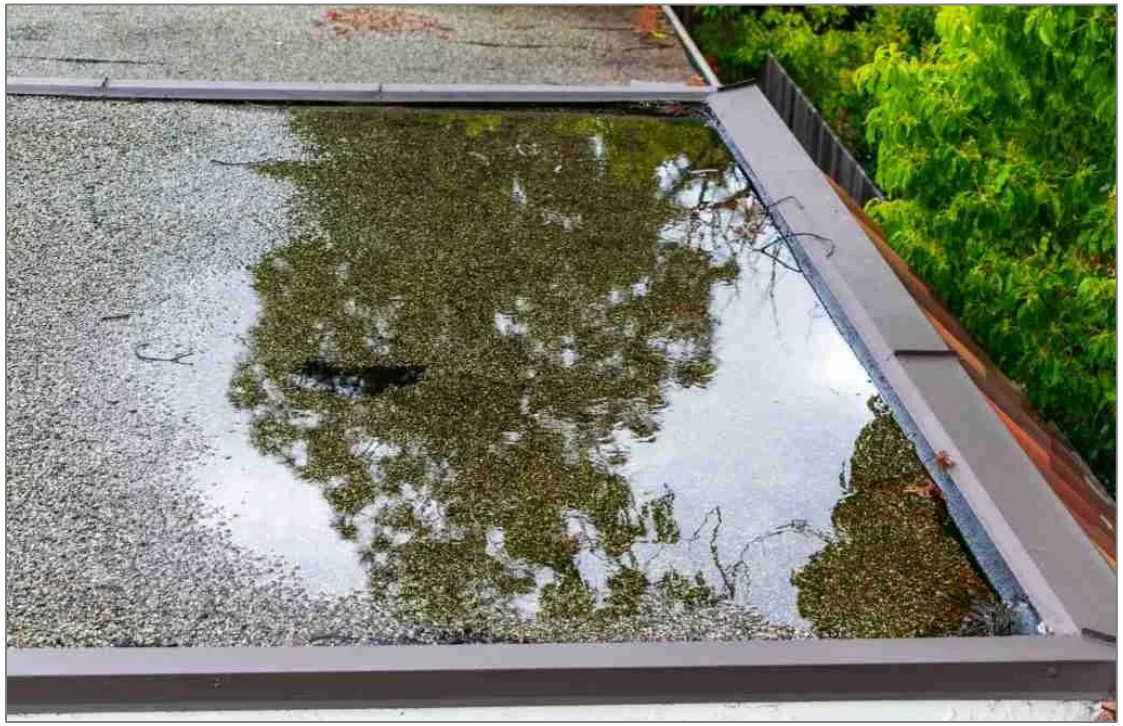
Action effects ≤ Structural resistance

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

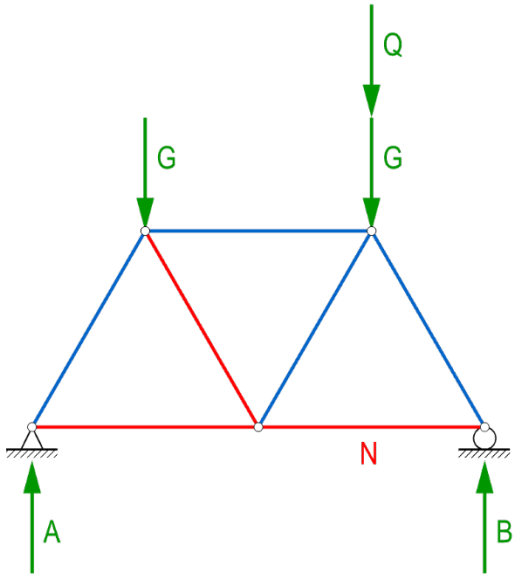
structural failure lead to important consequences

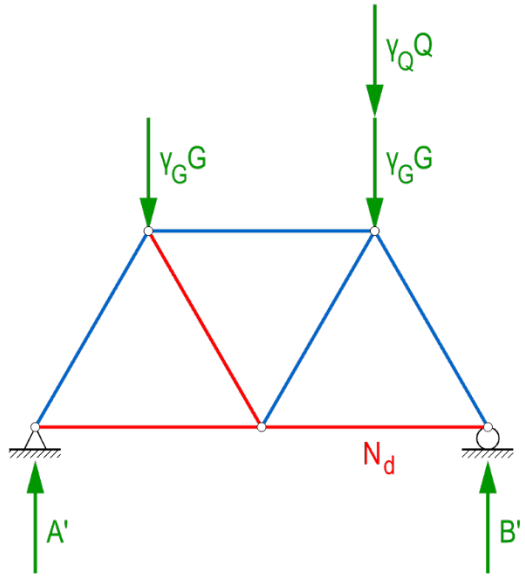
design values

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

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

› **Action effect N_{Ed}** obtained for given load combination



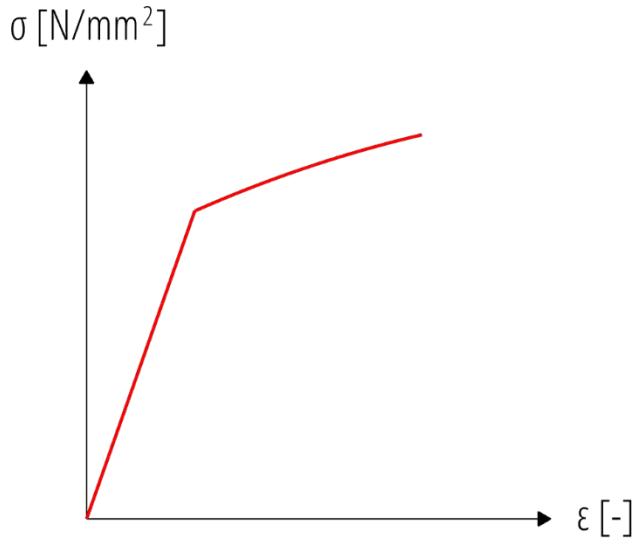


design values

› **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

embodied global warming potential

- the embodied carbon coefficient (ECC) covers emissions due to the **PRODUCTION** phase.
- Emissions due to transport, construction, use and end-of-life must also be considered in a full Life Cycle Analyis (LCA, next lecture)

$$\sum_{i=1}^{n} \underbrace{\text{embodied carbon coefficient (ECC)}}_{kg_{CO2eq} / kg_{material}} \times \underbrace{\text{material quantity}}_{kg_{material}} = \underbrace{\text{global warming potential (GWP)}}_{kg_{CO2eq}}$$

design of a structural element (including GWP)

inputs :

› geometry and actions

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

outputs :

› material volume
› material weight
› GWP

design of a structural element (including GWP)

GWP [kg_{CO2e}]

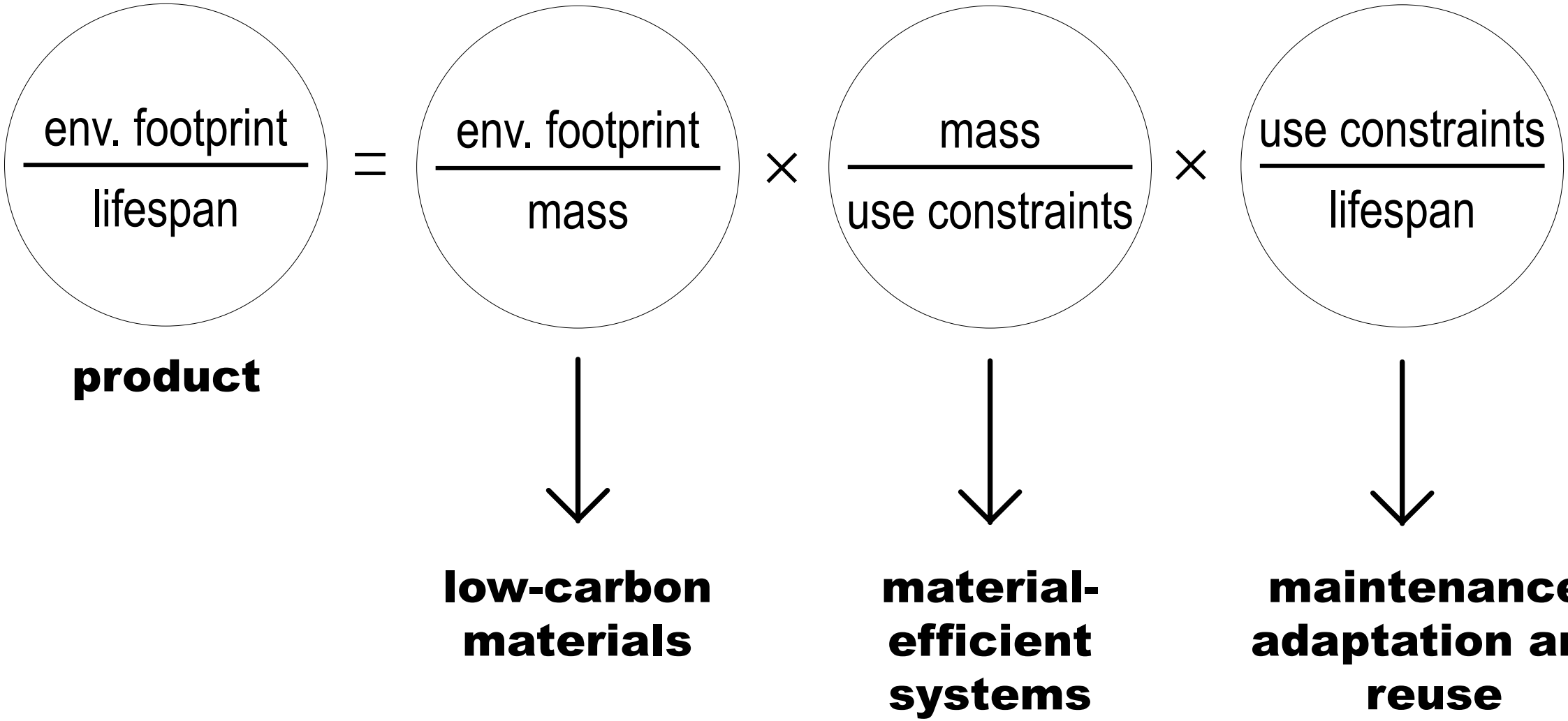
= **ECC** [kg_{CO2eq}/kg] × **weight** [kg]

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

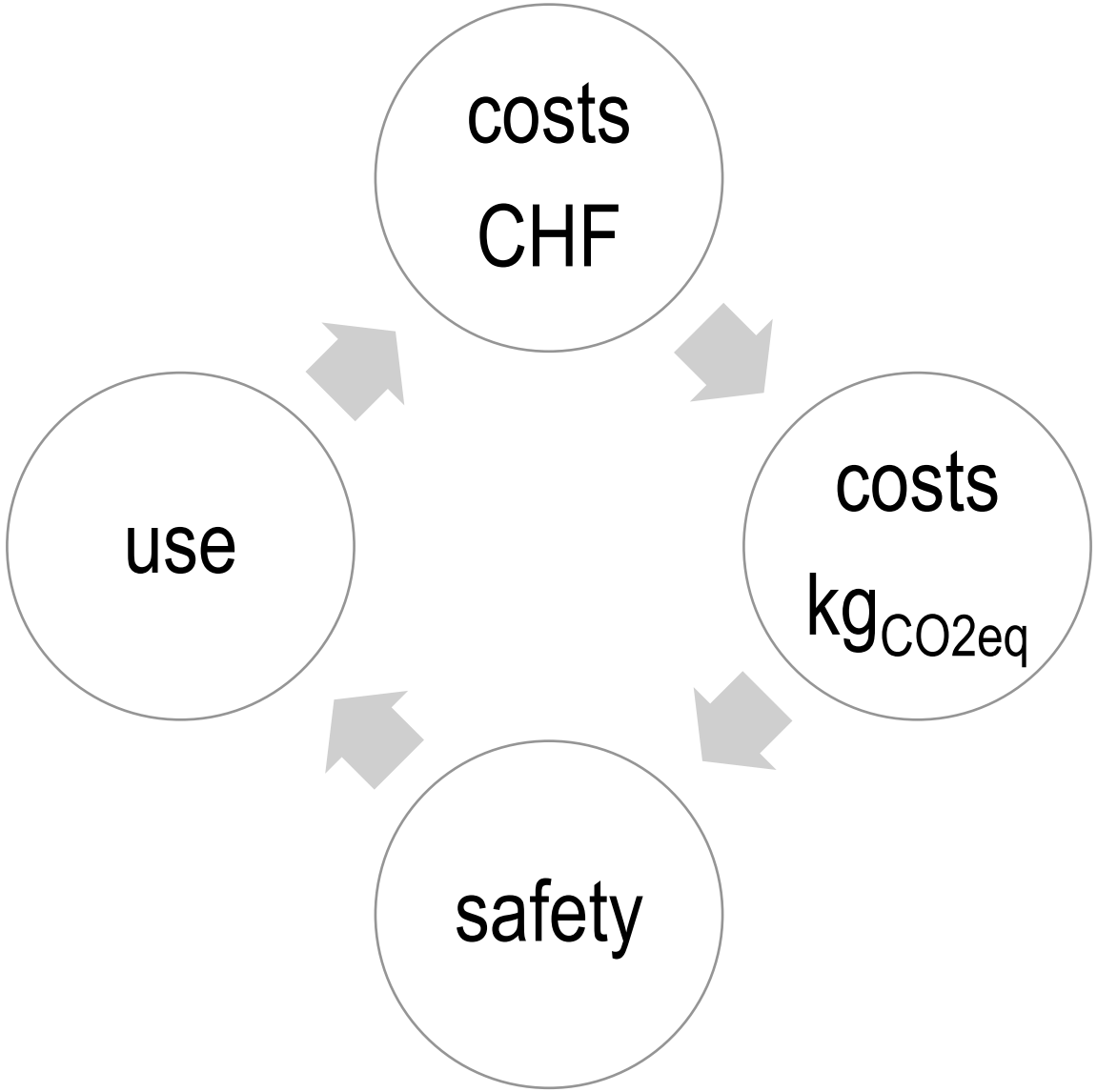
= **bar length** [m] × **cross-section area** [m^2]

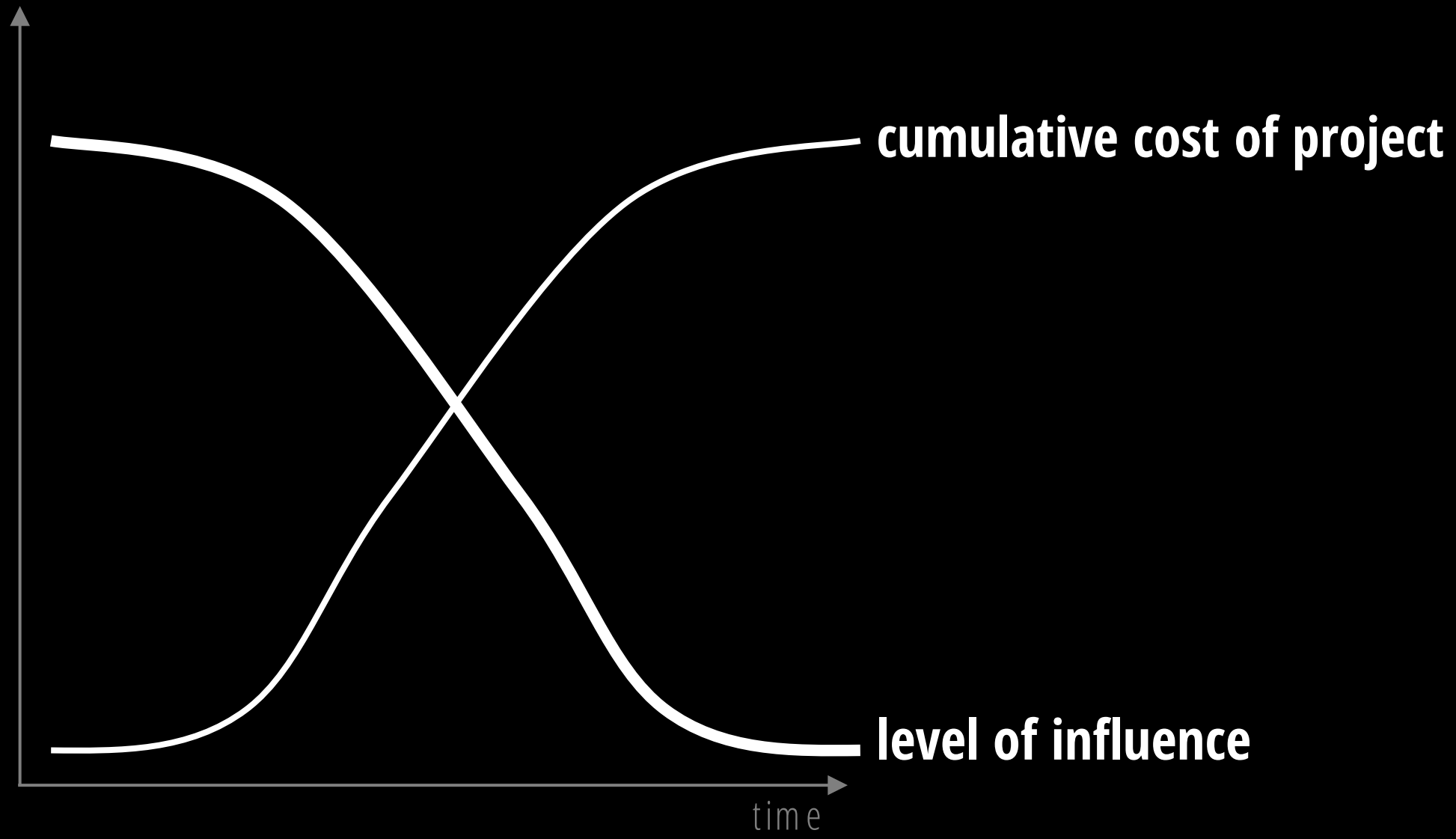
= **action** [kN] / **streght** [kN/m^2]

performance and design



performance and design





after Paulson “Designing to reduce construction costs”, 1976

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

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_{yk} = 235 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] / **streght** [kN/m^2]

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

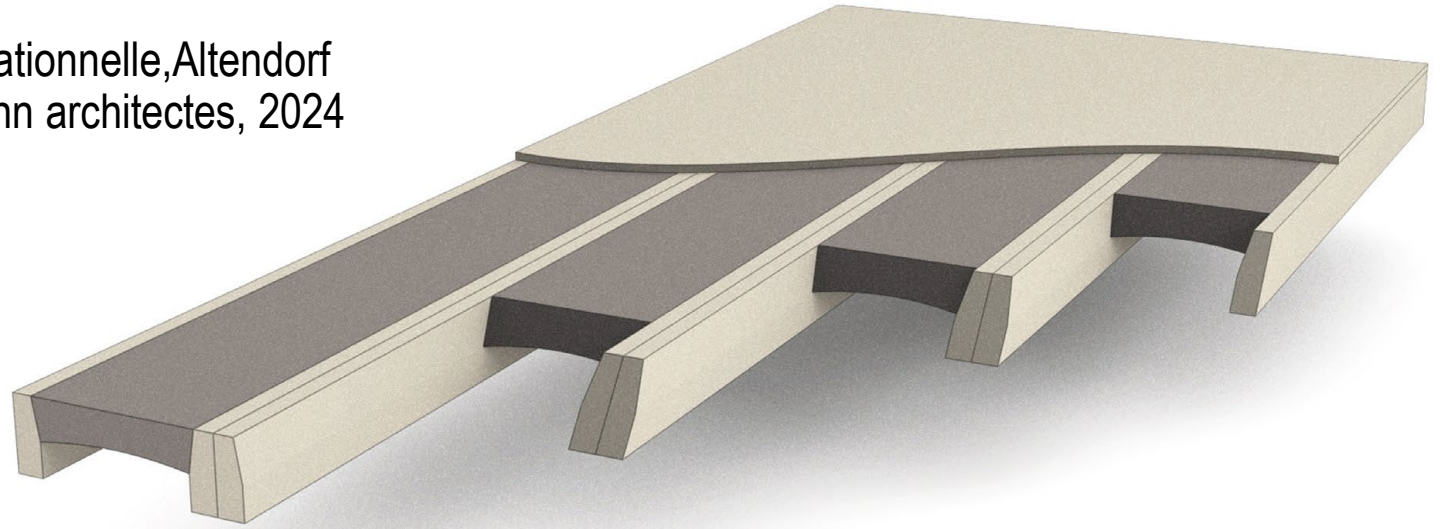
alternatives: geo-based materials

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



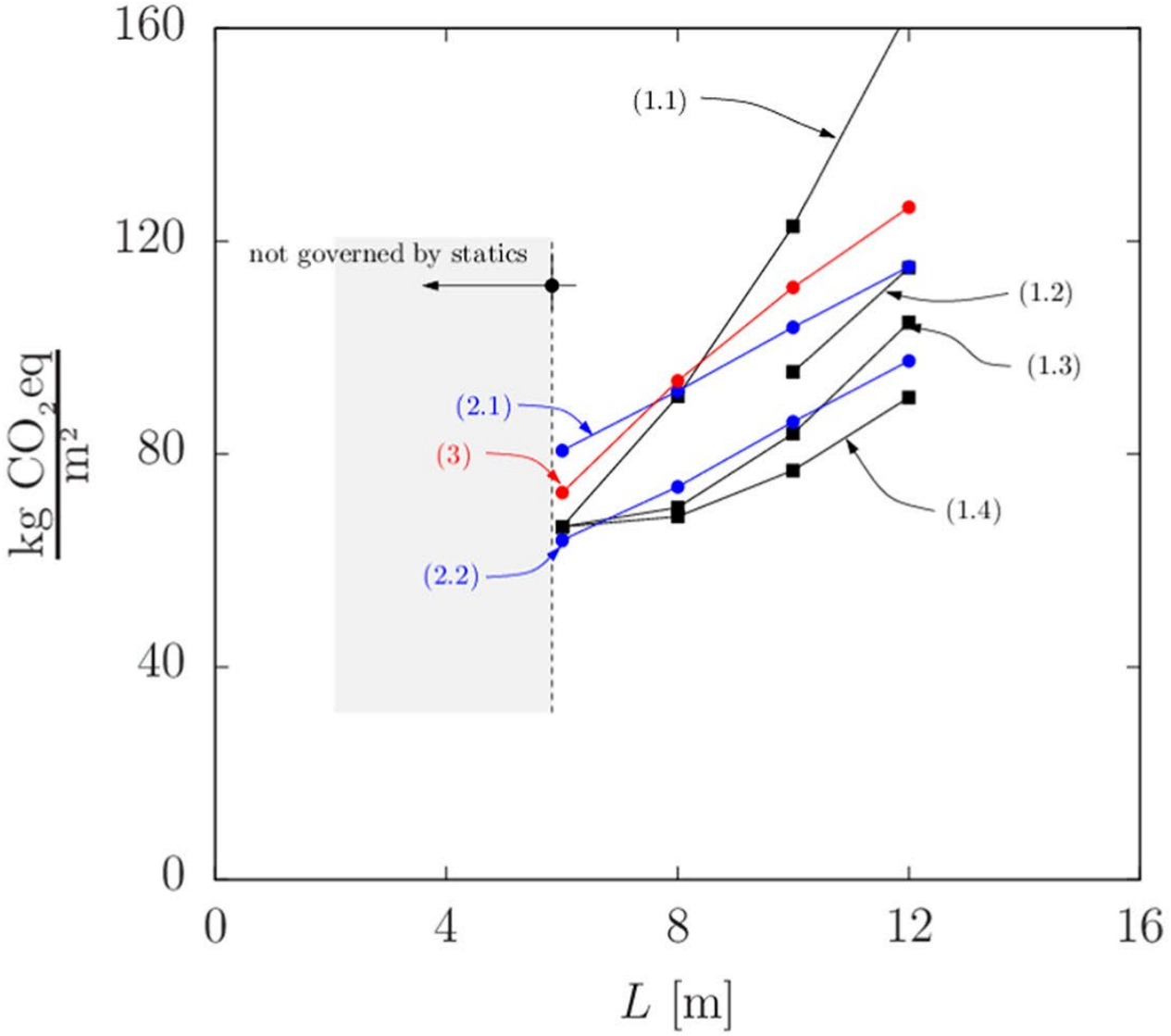
alternatives: geo-based materials

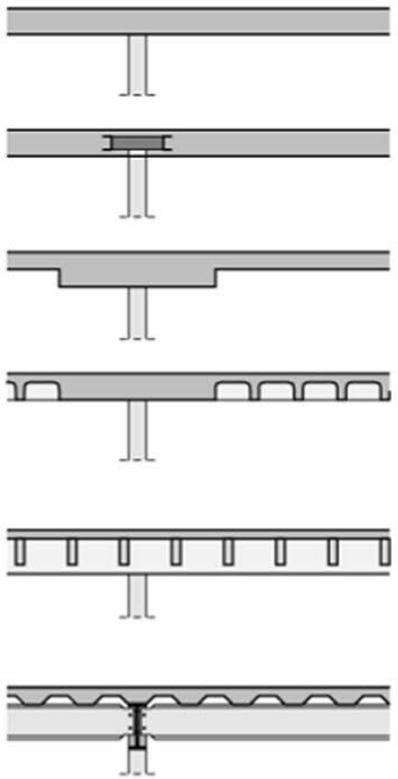
massiv stone masonry

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

structural systems

material choice and structural system





(1.1) reinforced concrete flat slab

(1.2) prestressed flat slab with shearheads

(1.3) flat slab with drop panels

(1.4) waffle slab

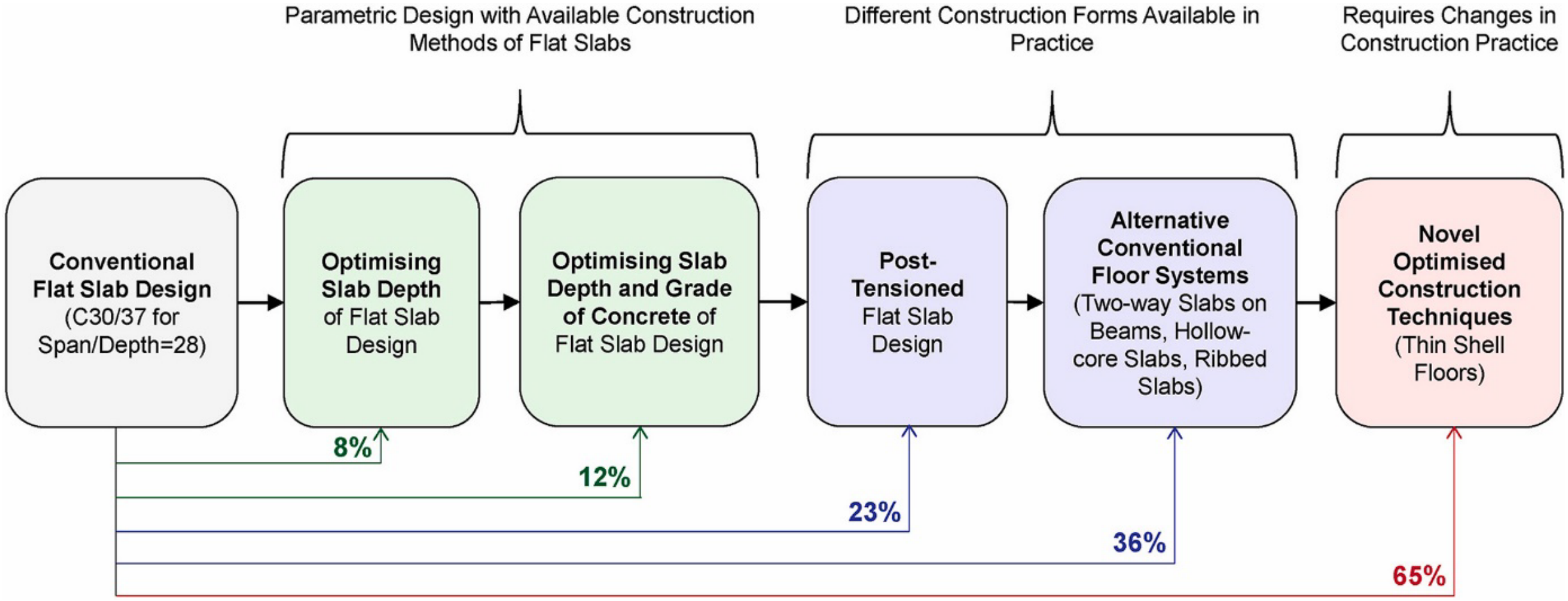
(2.1) timber-concrete composite

(2.2) full timber

(3) steel-concrete composite

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

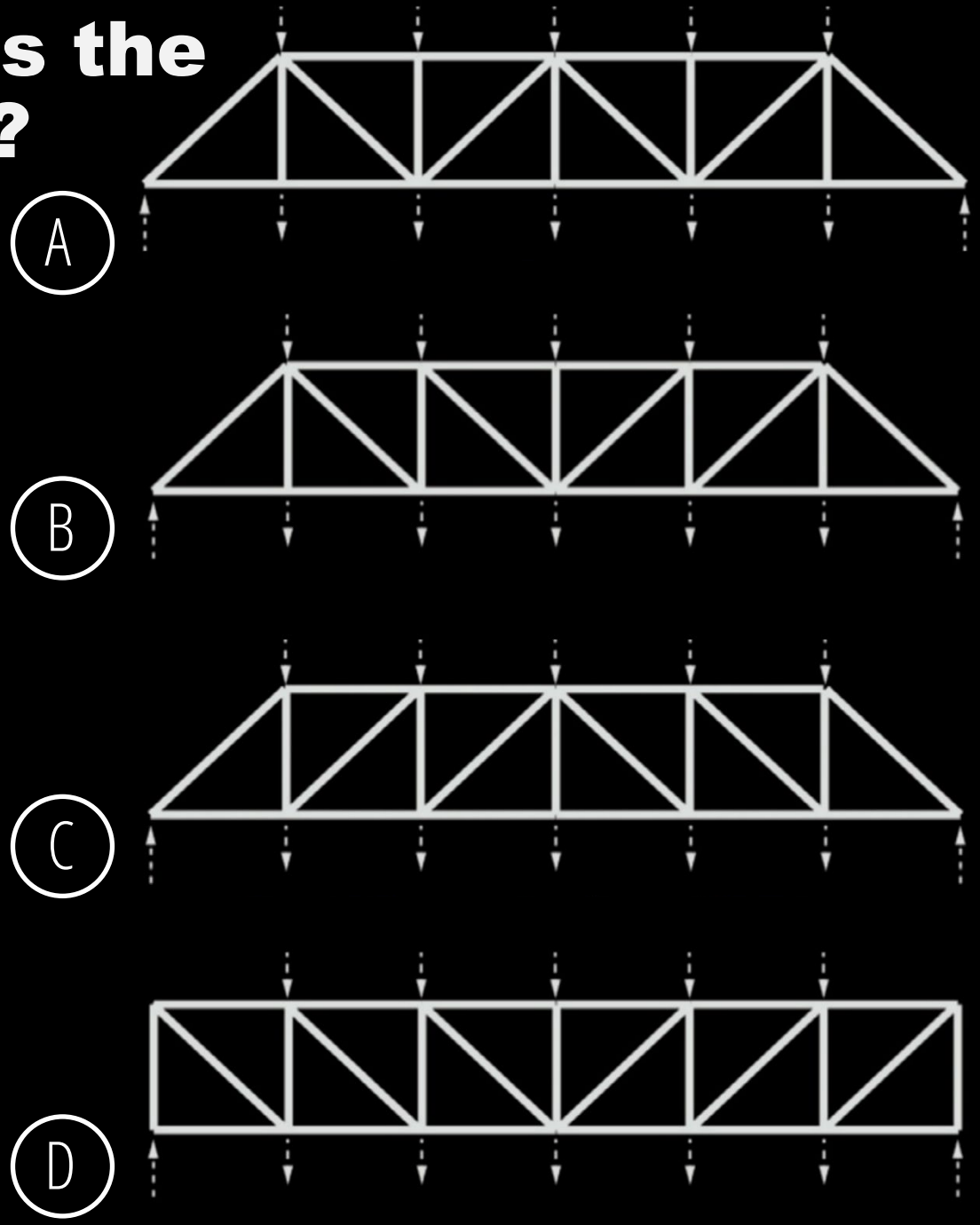
optimisation of structural system



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.

structural topology

POLL: what topology requires the greatest amount of material?



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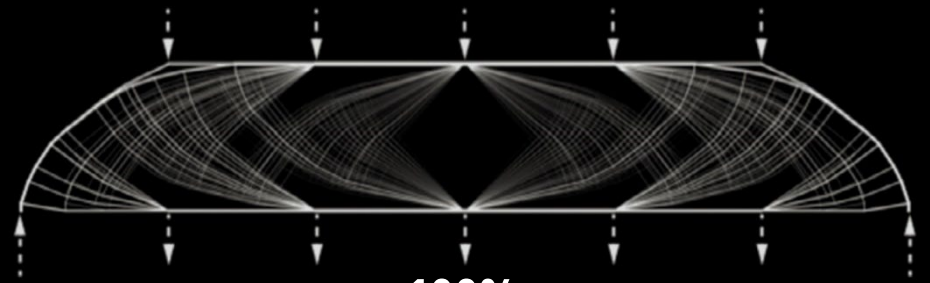
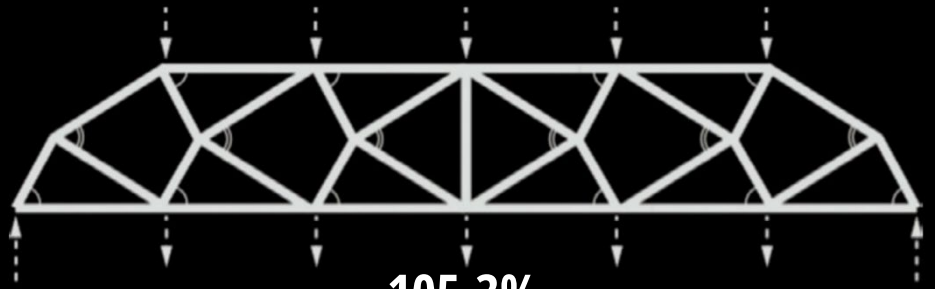
structural topology



100%



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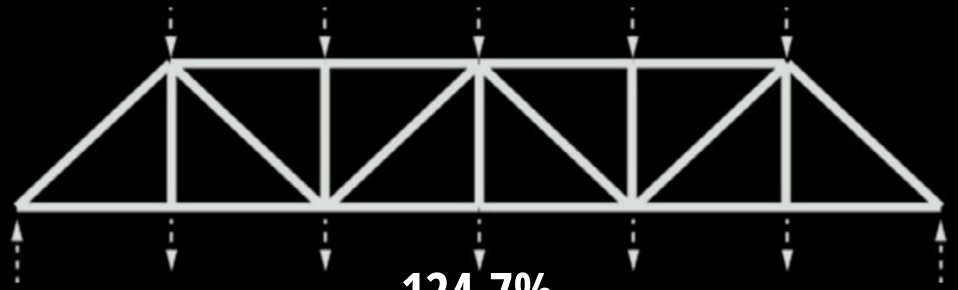
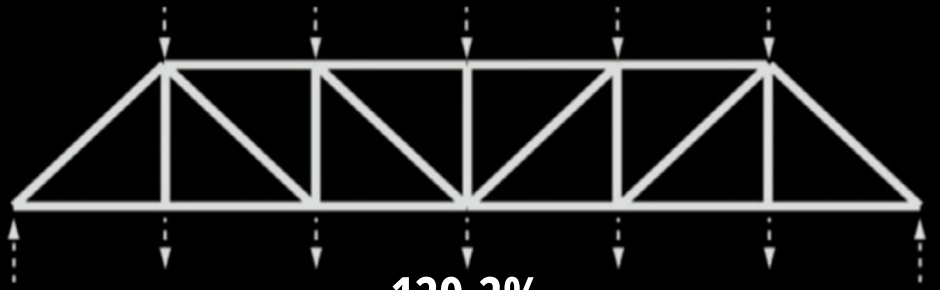
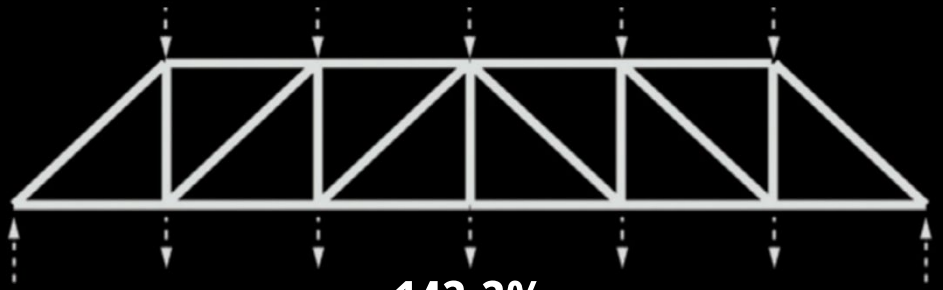


124.7%



129.2%



143.3%

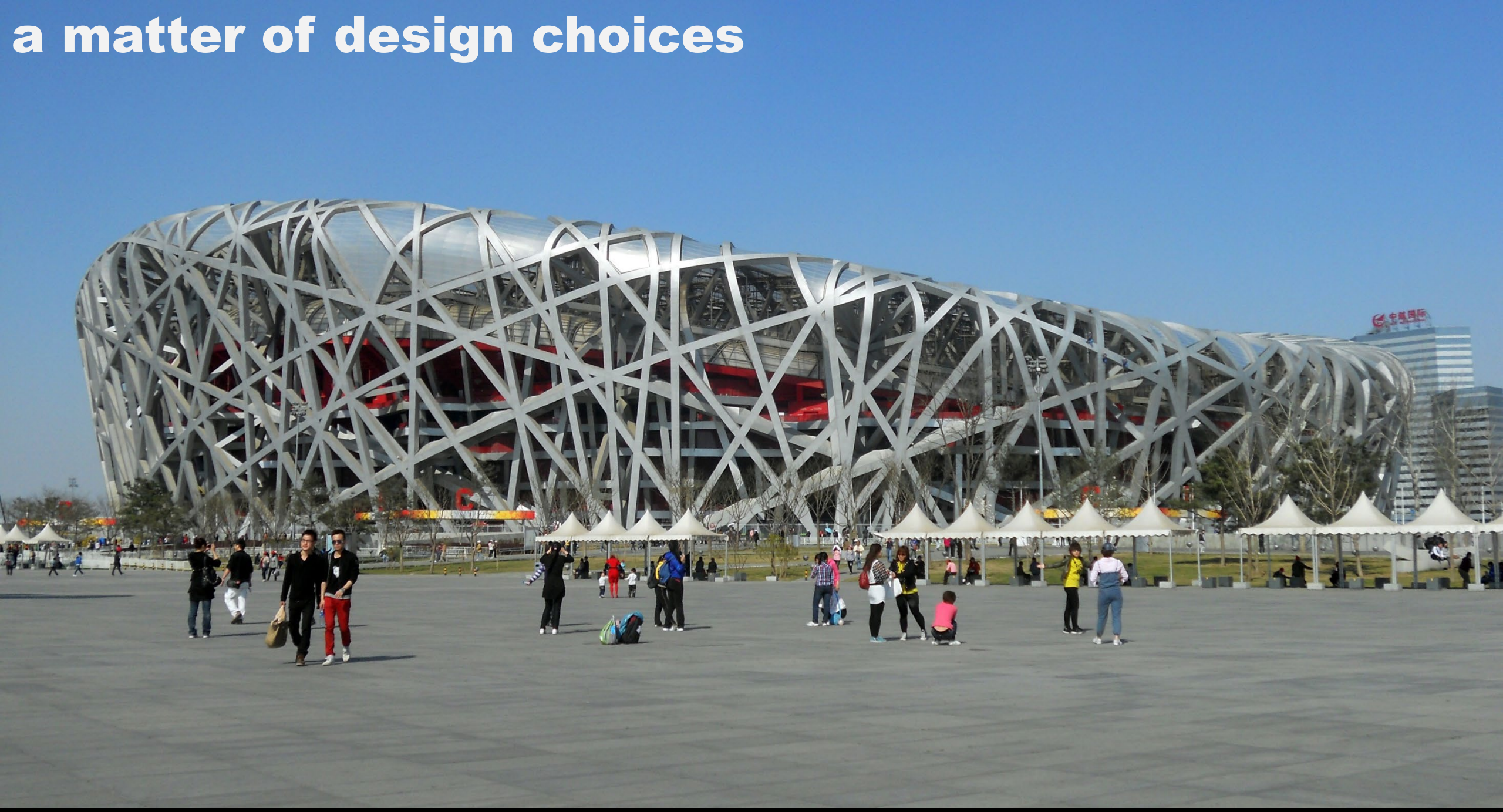
168.4%

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

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?

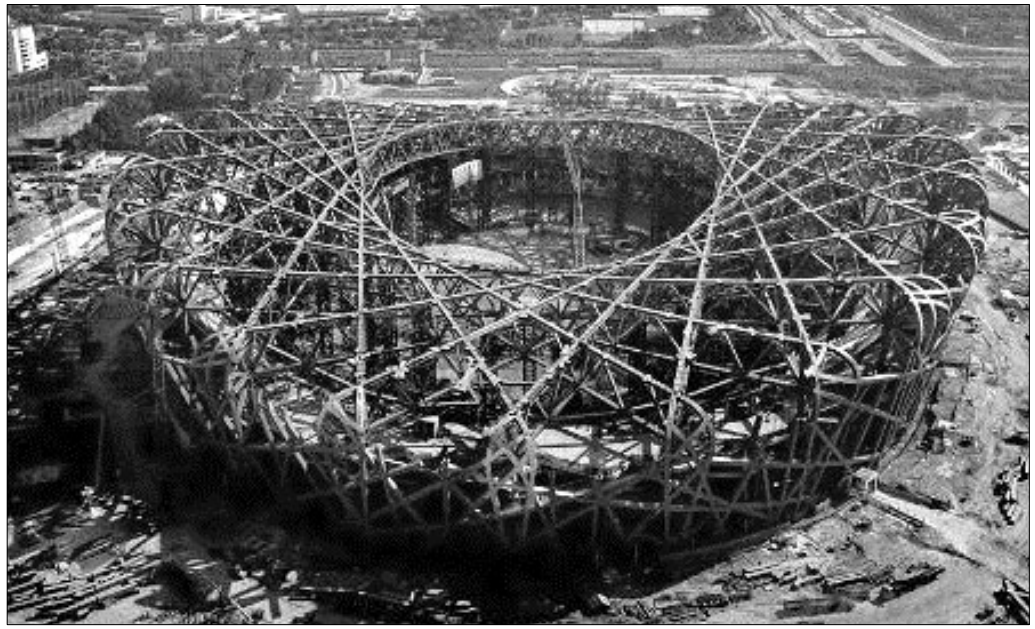
A

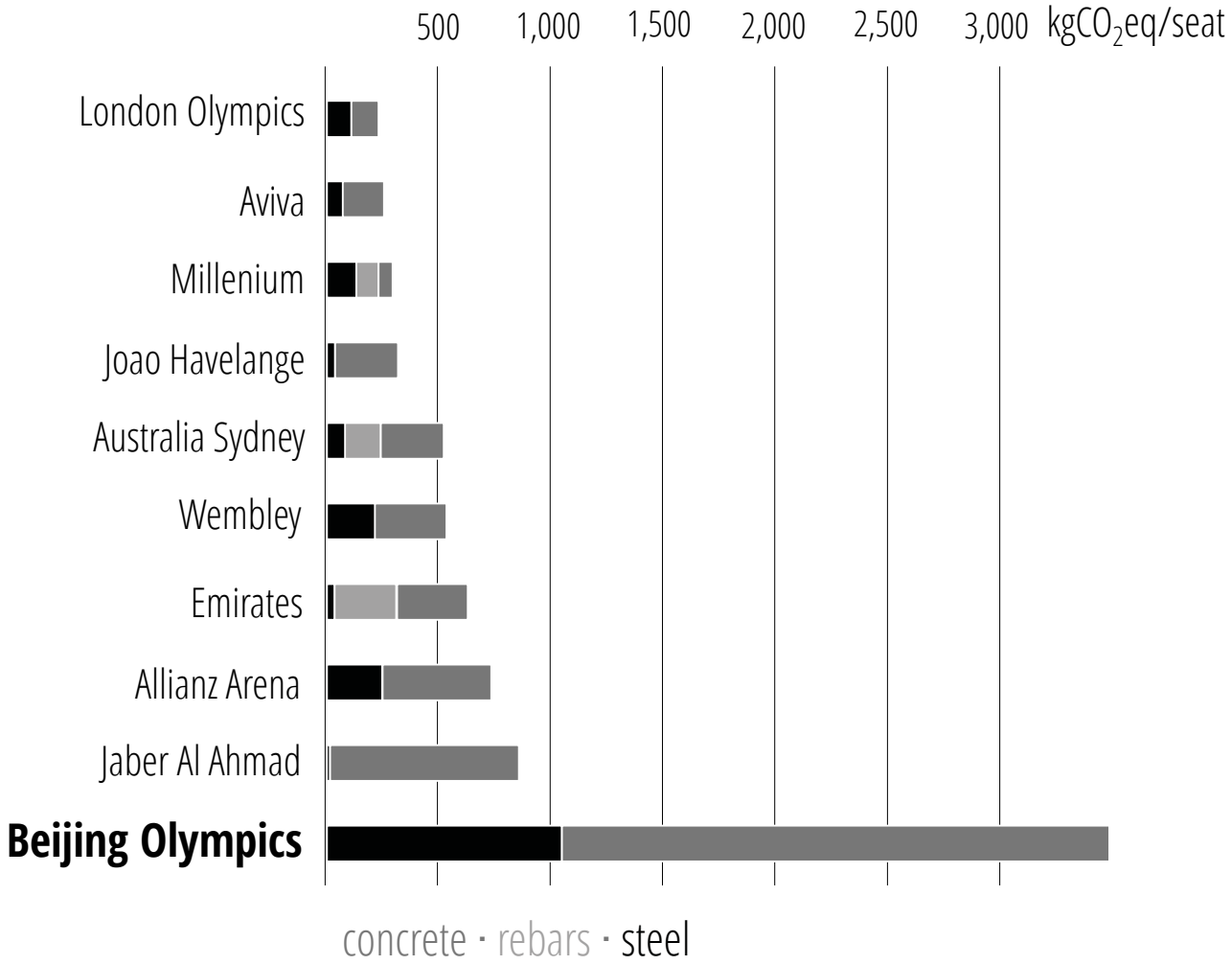
B

C

Join at
slido.com
#2030 357

embodied carbon per seat

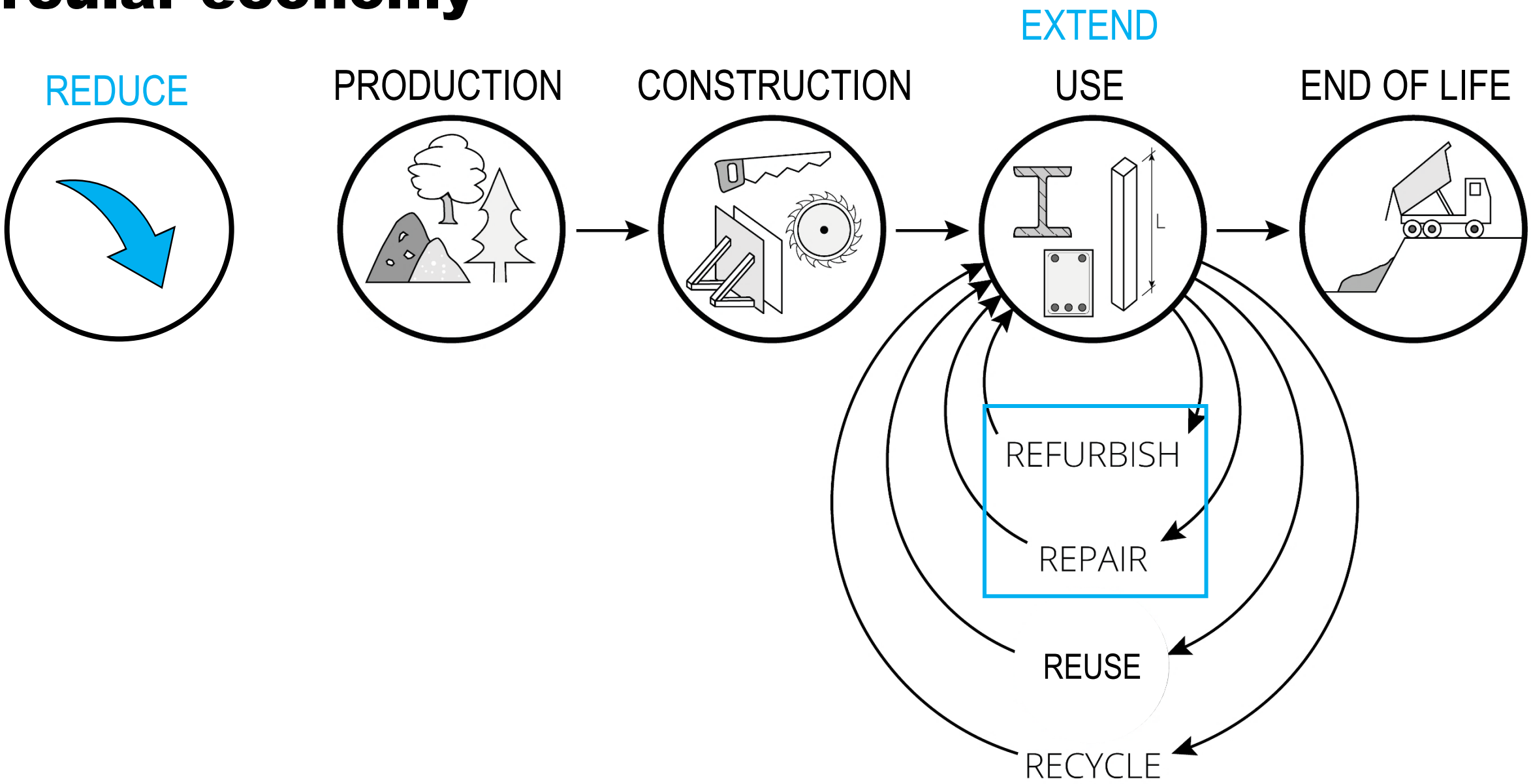




De Wolf et al. · Comparing material quantities and embodied carbon in stadia · IASS 2014

lifespan

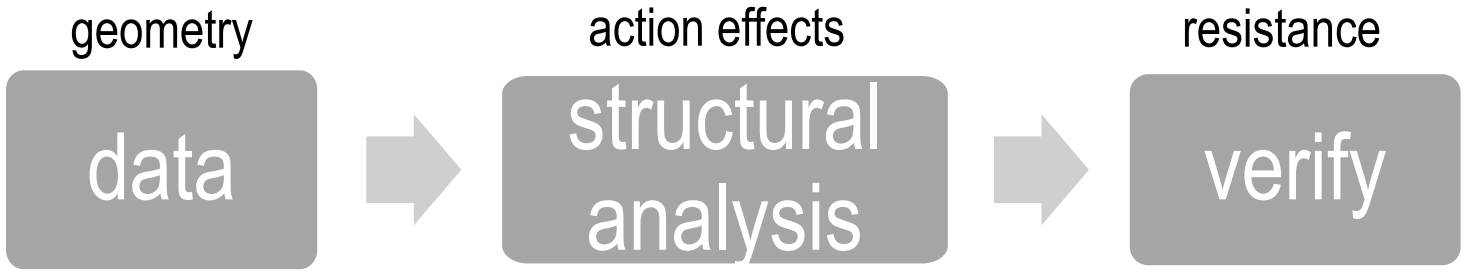
circular economy



extend the lifespan 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



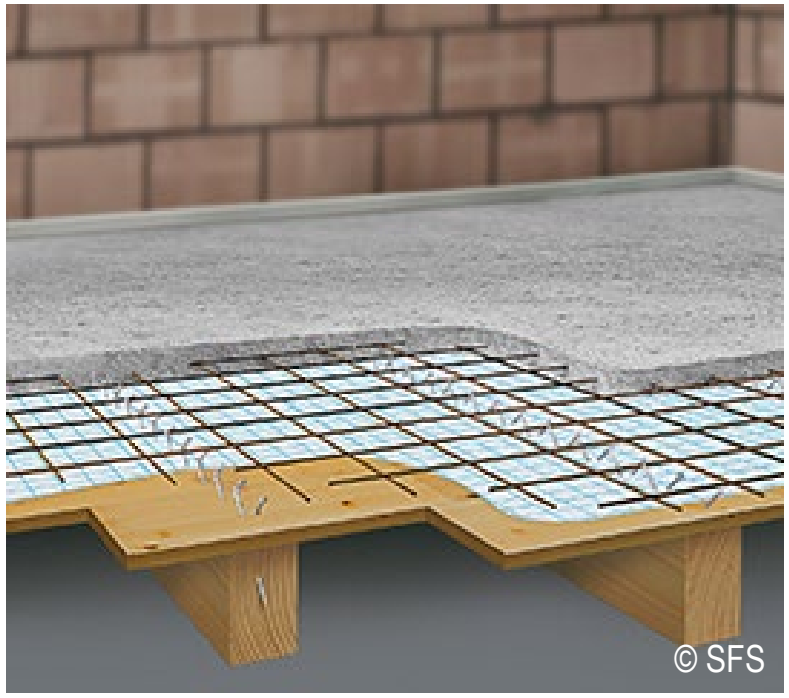
strengthening of structures

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

UHPFRC layer

carbon lamella

concrete overlay



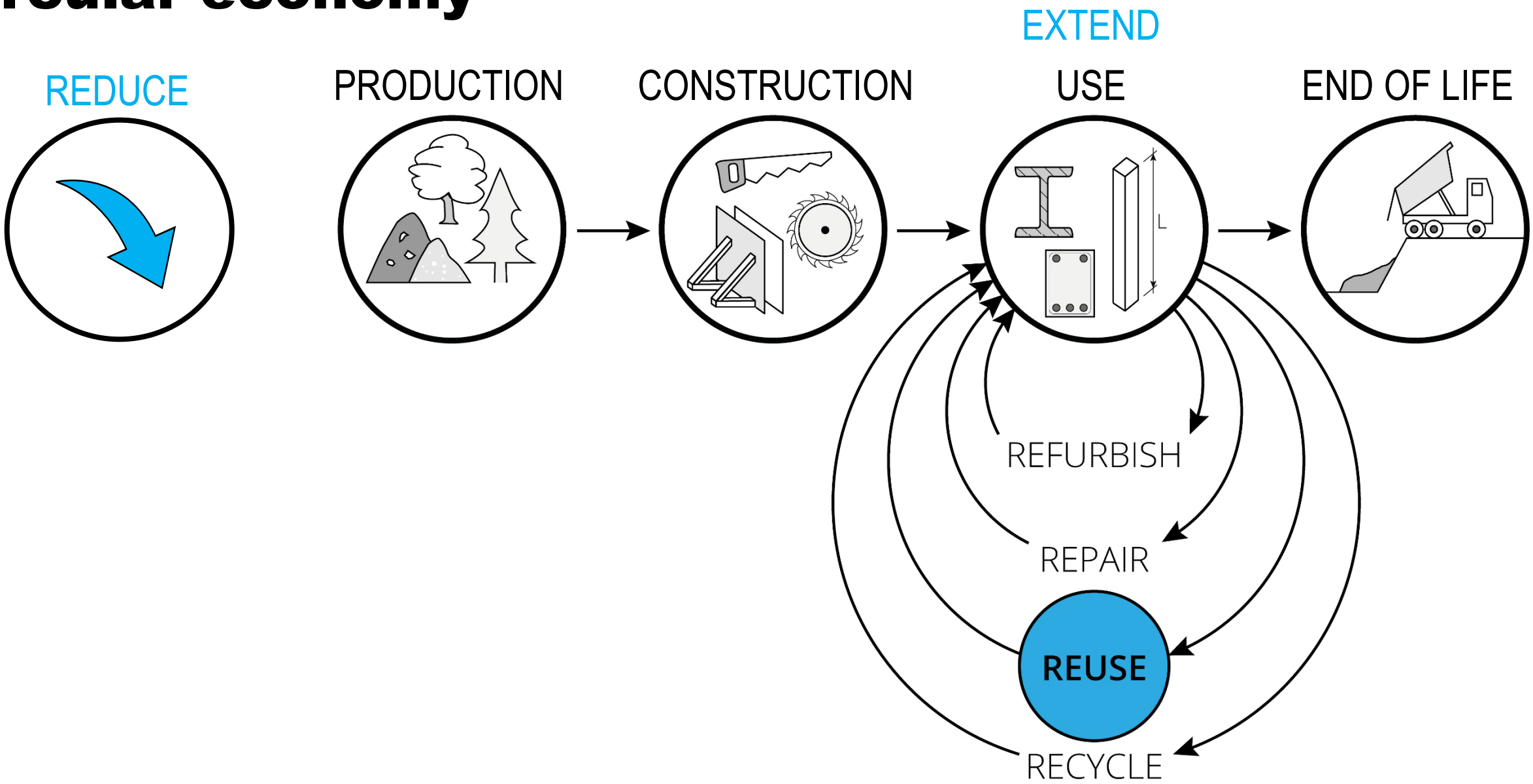
Any transformation has an environmental cost, generally lower than the cost of demolition/reconstruction!

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



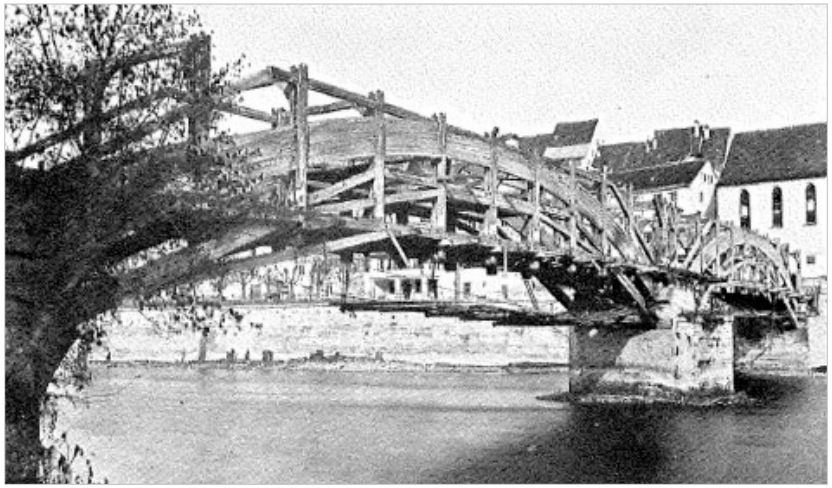
commonplace

Genève, 1898 © Boissonnas, Bibliothèque de Genève

reuse of construction components

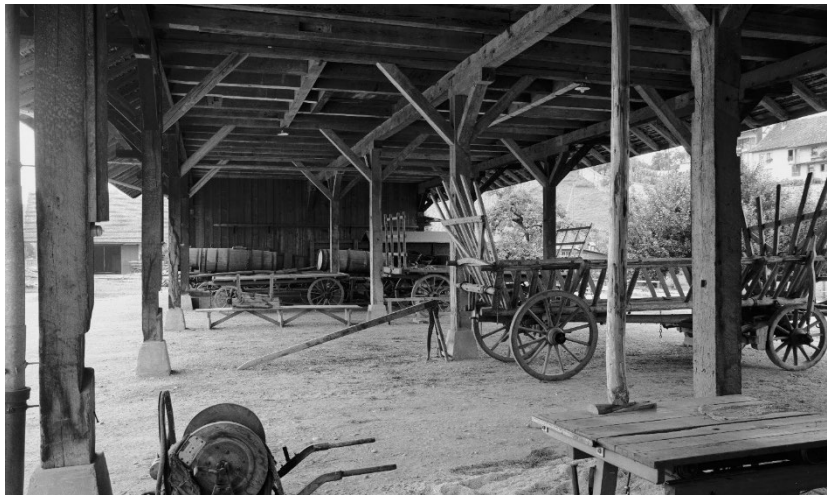
1810

1919



Eglisau, CH

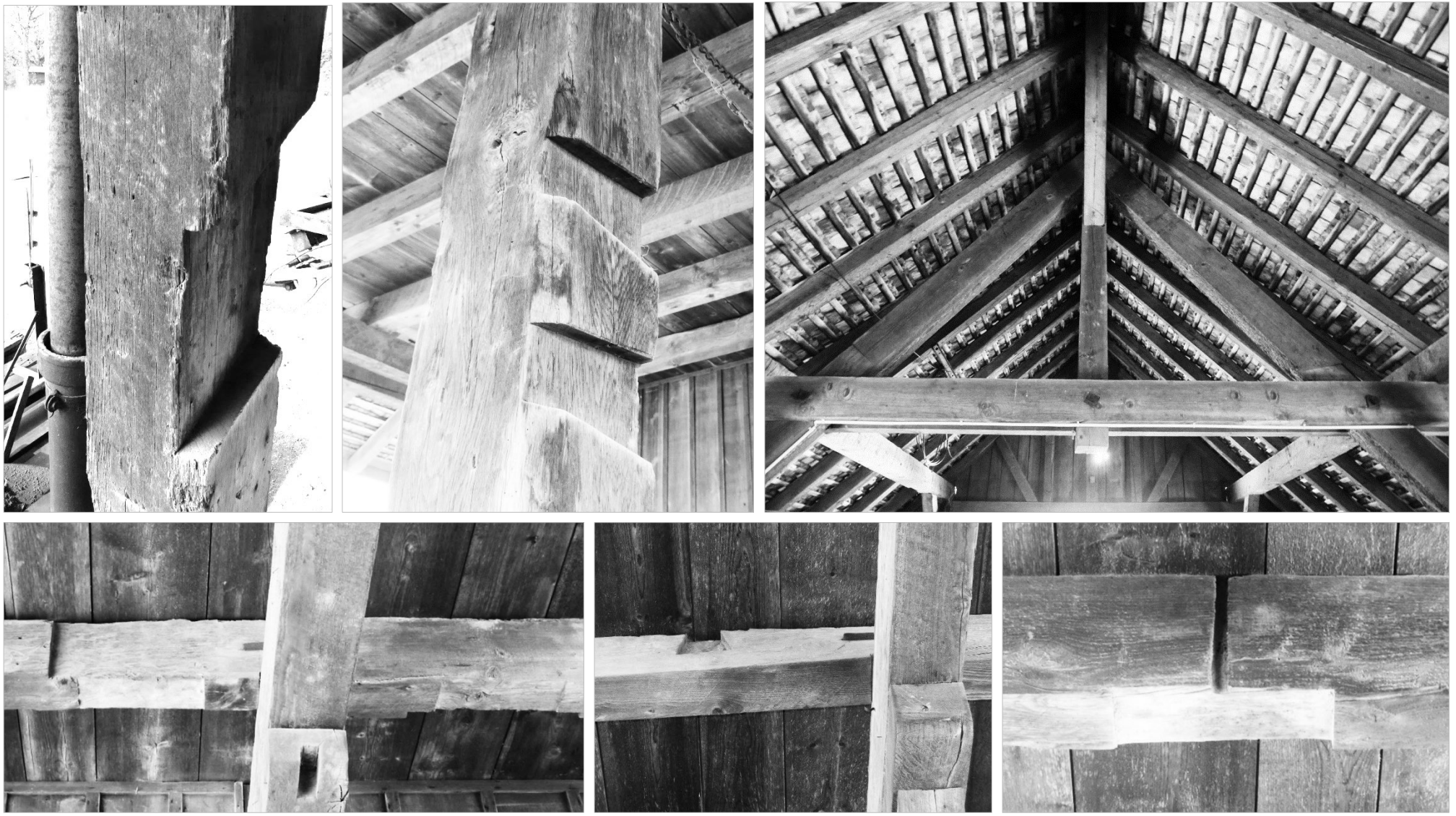
Rheinau, CH



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



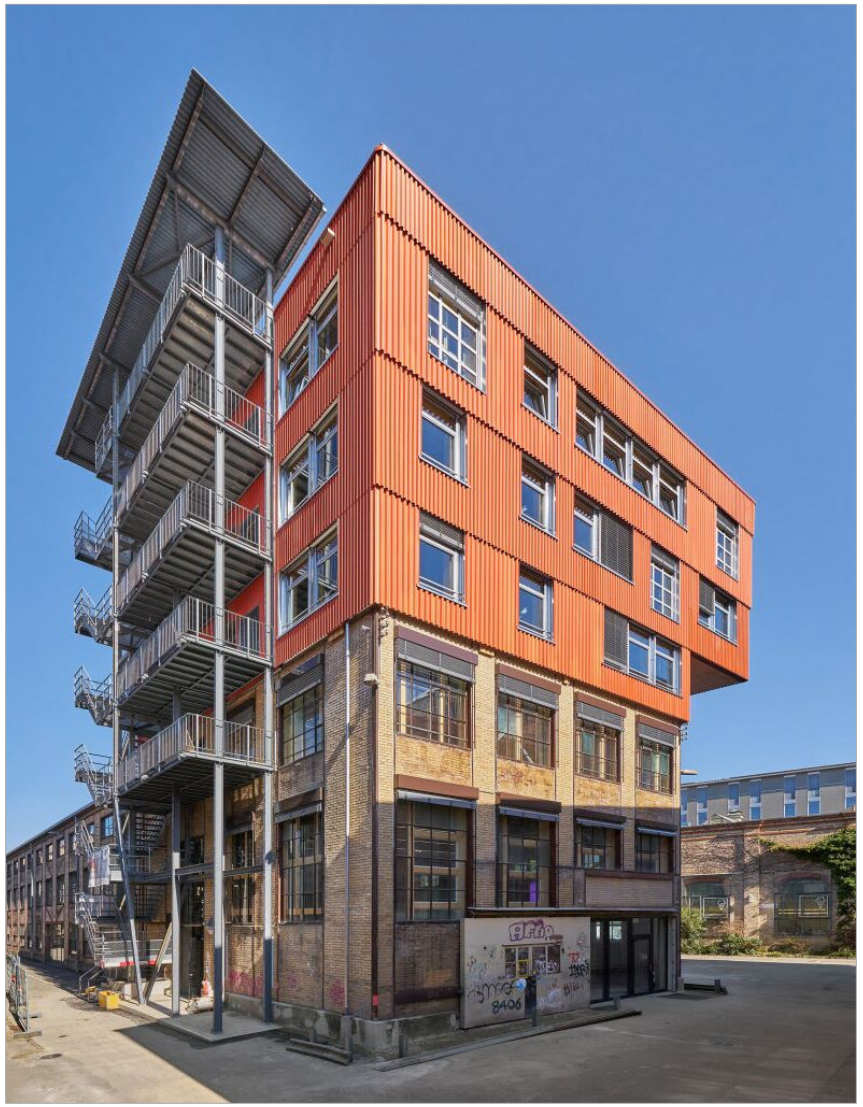
C.Fivet, J.Brütting · Nothing is lost, nothing is created, everything is reused - The new structural design assignment for the circular economy · 2019

recent example

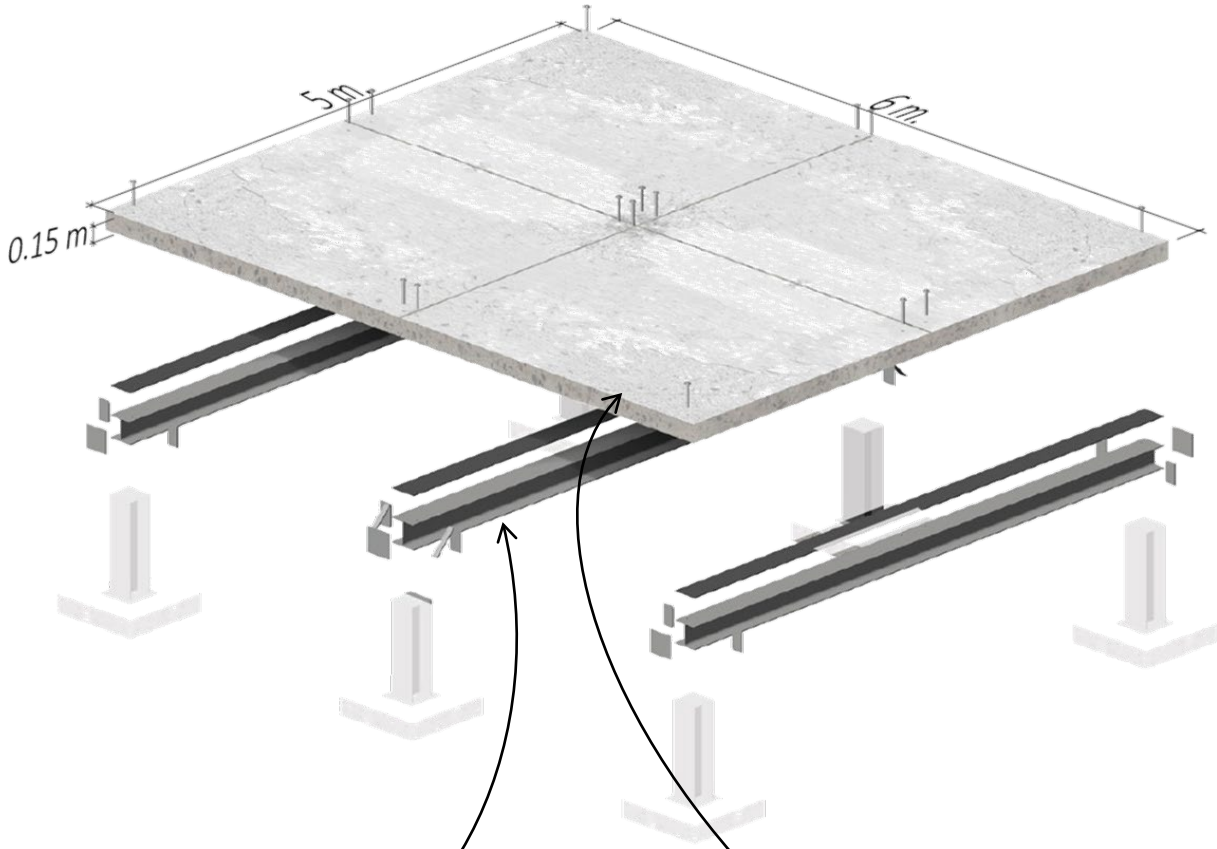
bâtiment existant

approvisionnement

rehabilitation et réemploi



reclaimed floor system



reclaimed
steel beams

saw-cut
reinforced concrete
slabs

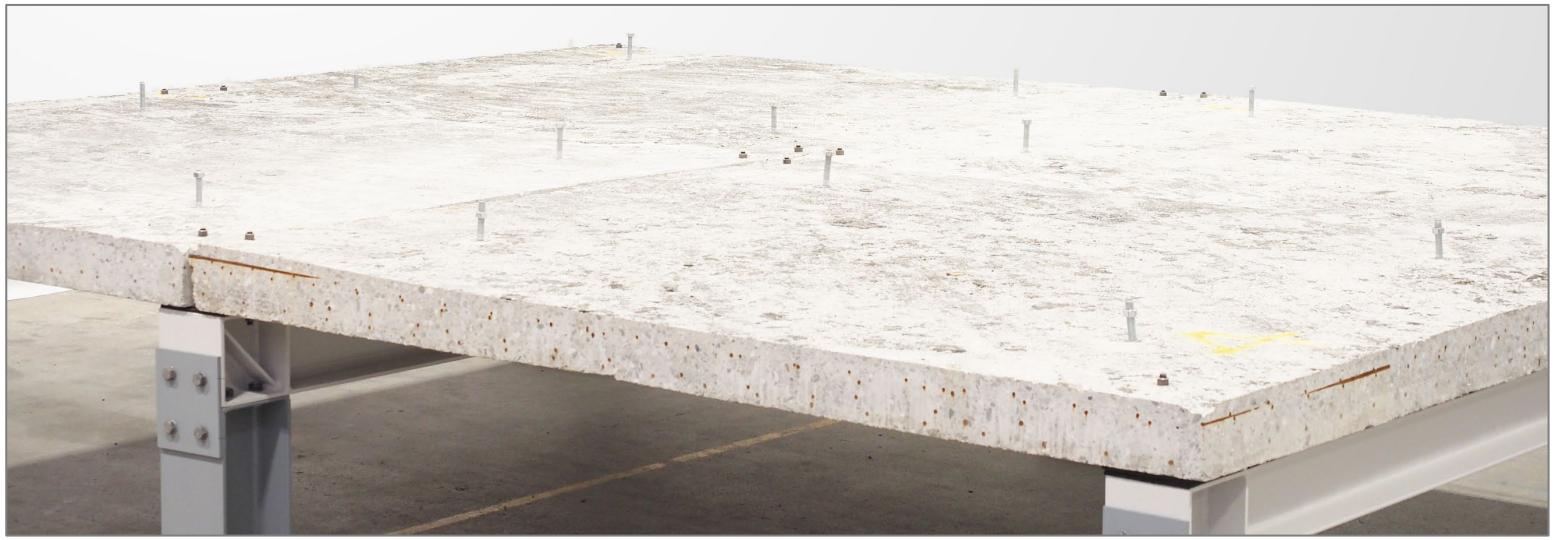
roof slab

steel frame

construction process

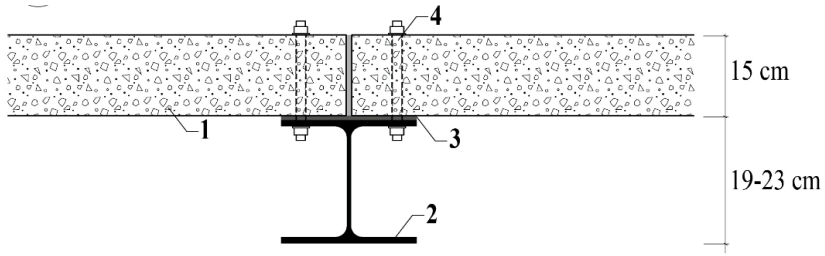




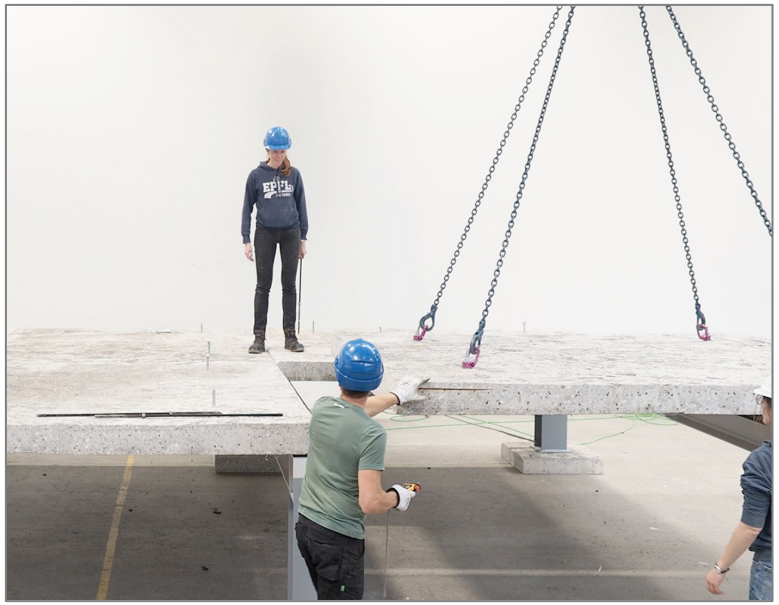


Küpfer et al. · Flo:Re – Floor made of REused concrete and steel · 2023

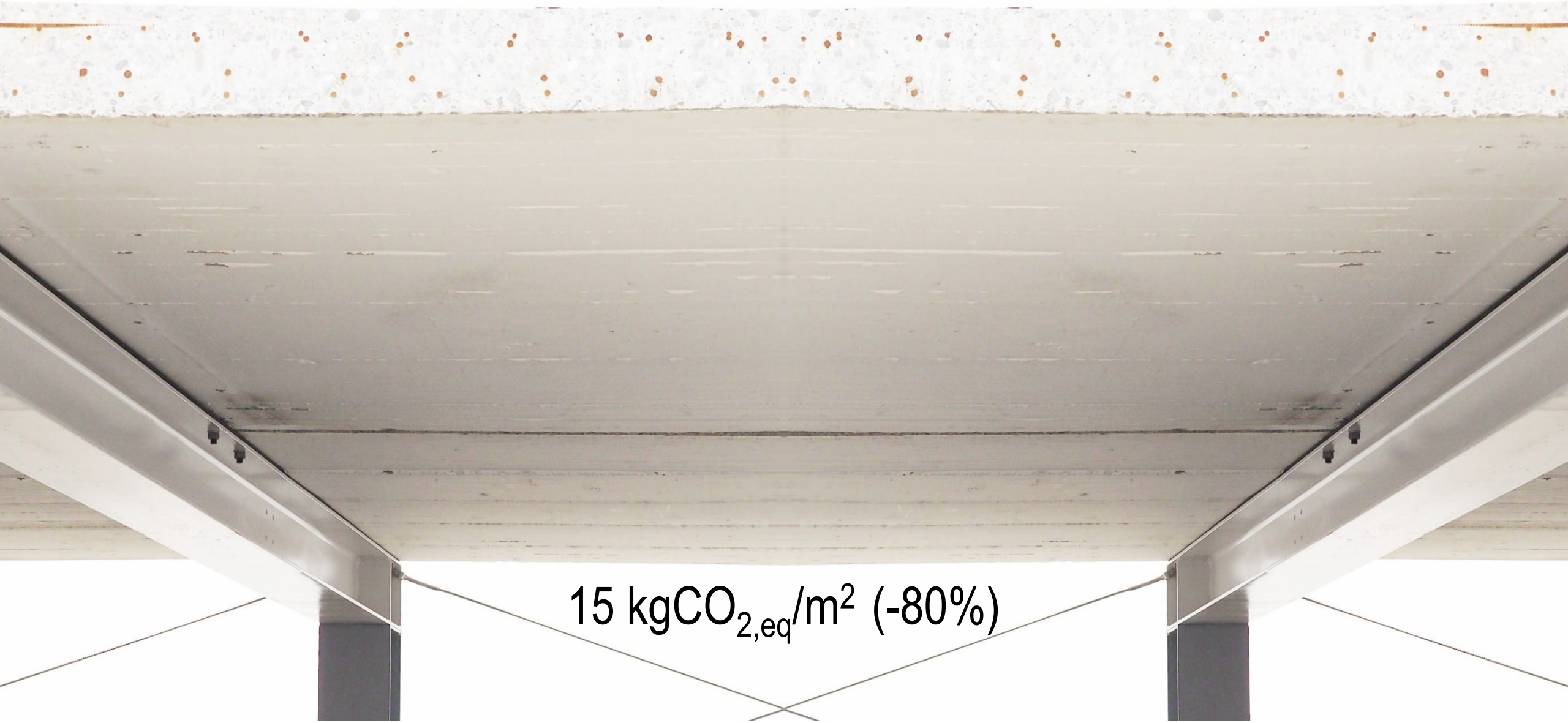
dry connections



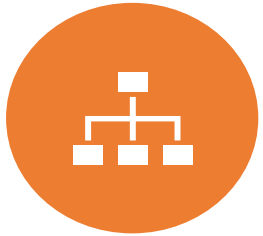
1 Reused 15-cm saw-cut reinforced-concrete slab (3 m x 2.5m)
2 Reused steel profile (HEA 200 and HEA 240) (5 m)
3 8-mm recycled rubber
4 ø16-mm prestressed threaded rod



ultra-low carbon slab



session recap



LIFE PHASES OF STRUCTURES

BASICS OF STRUCTURAL DESIGN

MATERIALS

STRUCTURAL SYSTEMS

LIFESPAN