Structural Design & Environmental Impact

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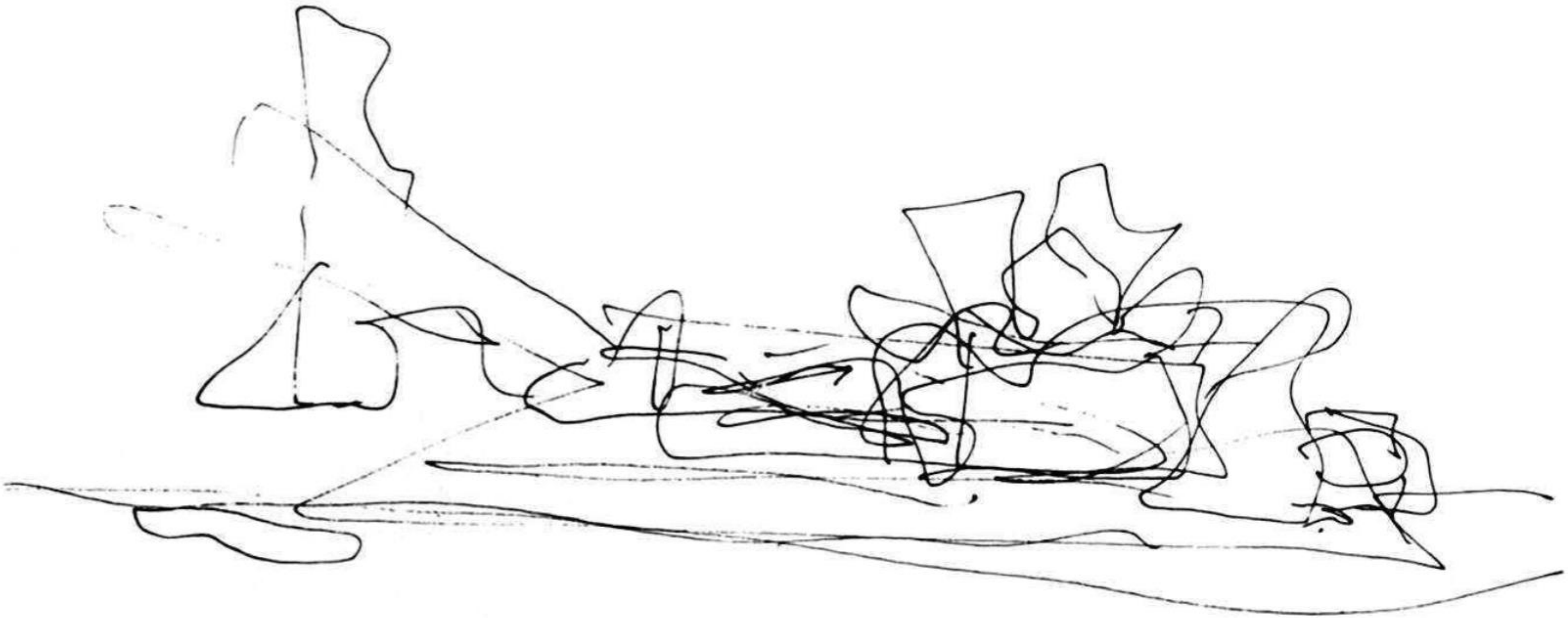
Dr. ès sc. – Postdoctoral researcher, Structural Engineer

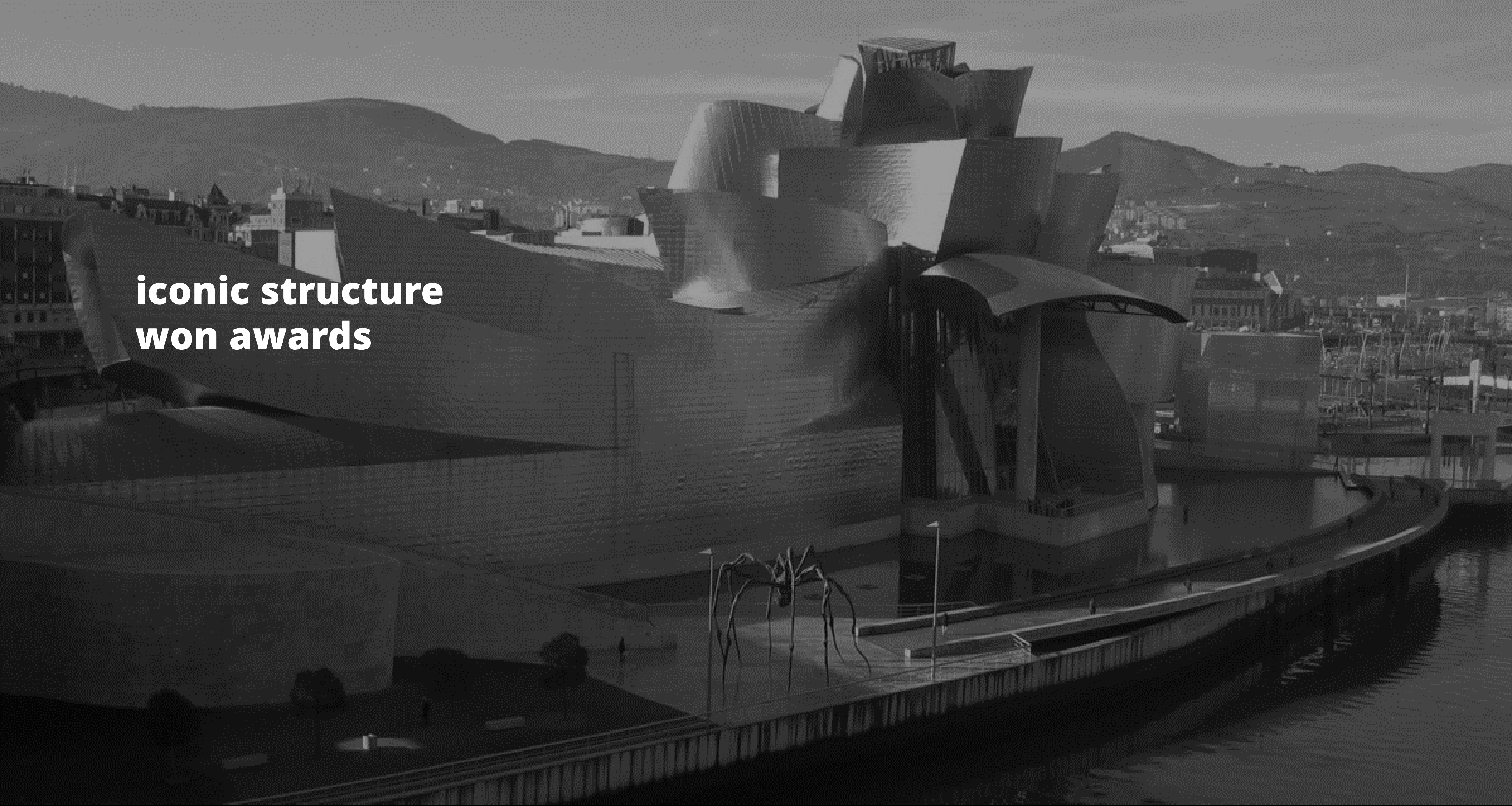
EPFL

PENS-313 26.02.25

STRUCTURAL XPLORATION LAB

context





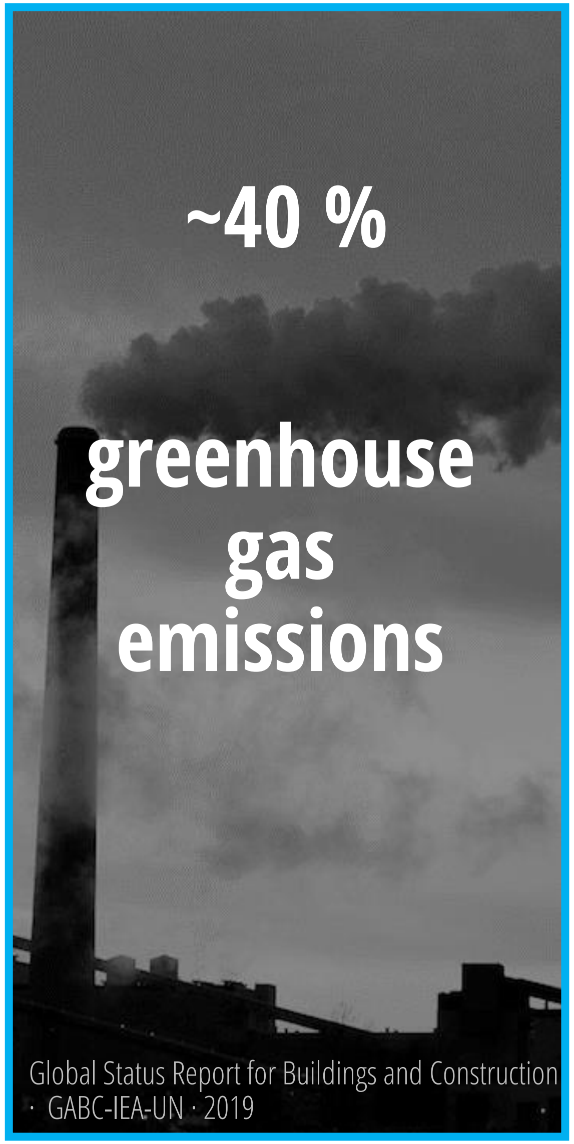
Frank O. Gehry – Guggenheim Museum – Bilbao, 1997

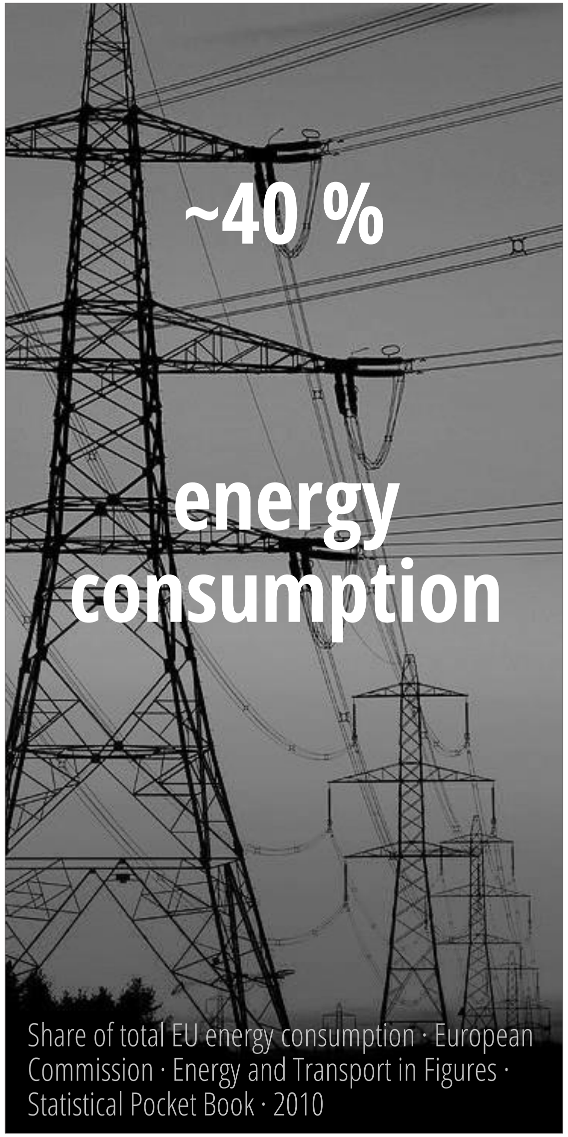
inefficient loadbearing
material intensive
cost intensive

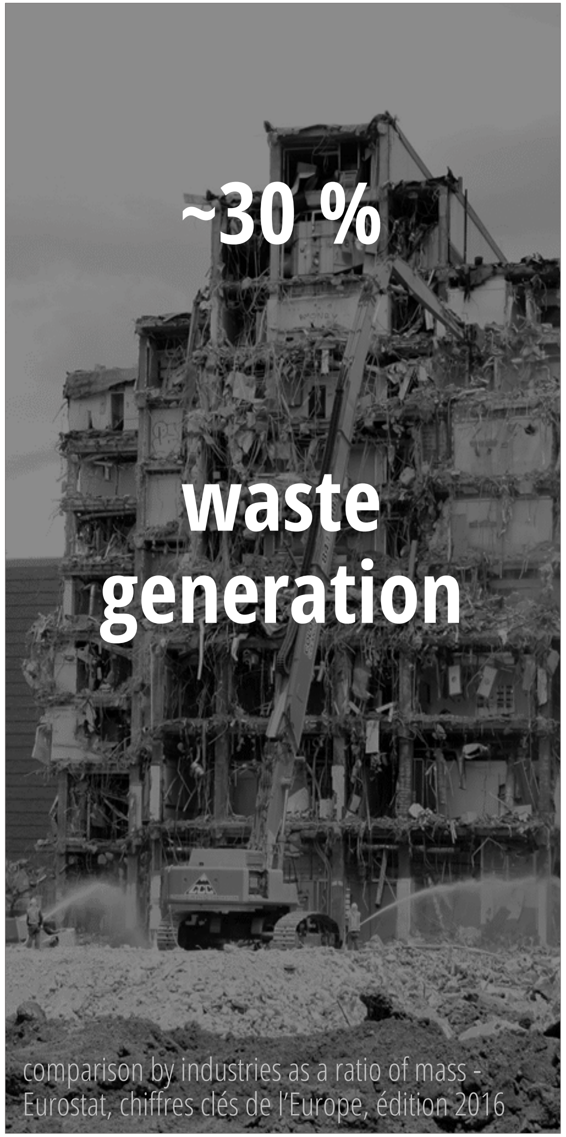
Why might this be an issue?

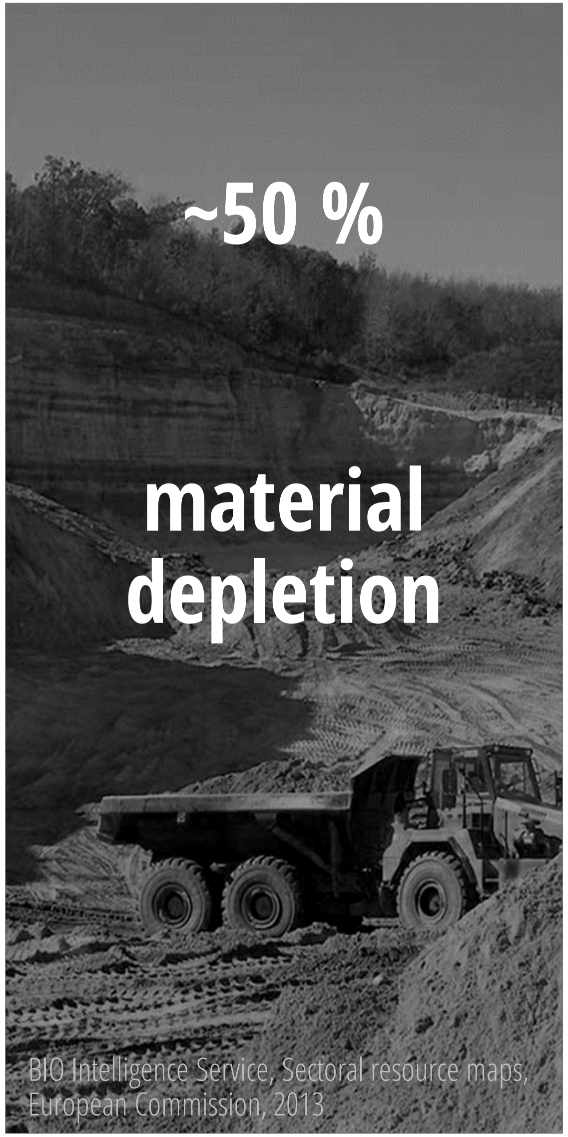
Frank O. Gehry – Guggenheim Museum – Bilbao, 1997

environmental toll of the built environment

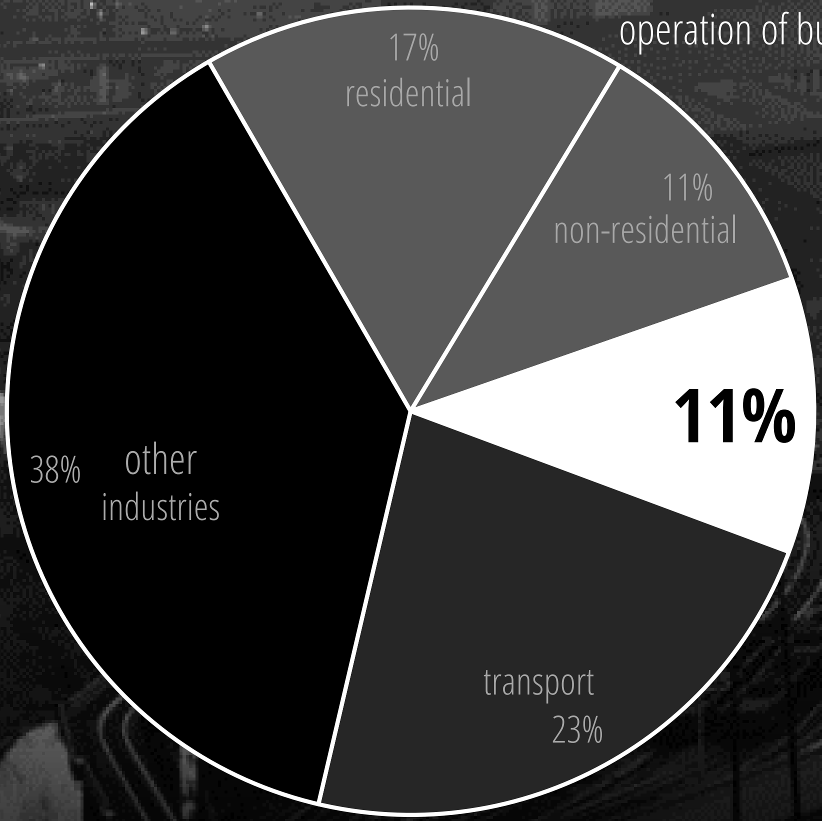




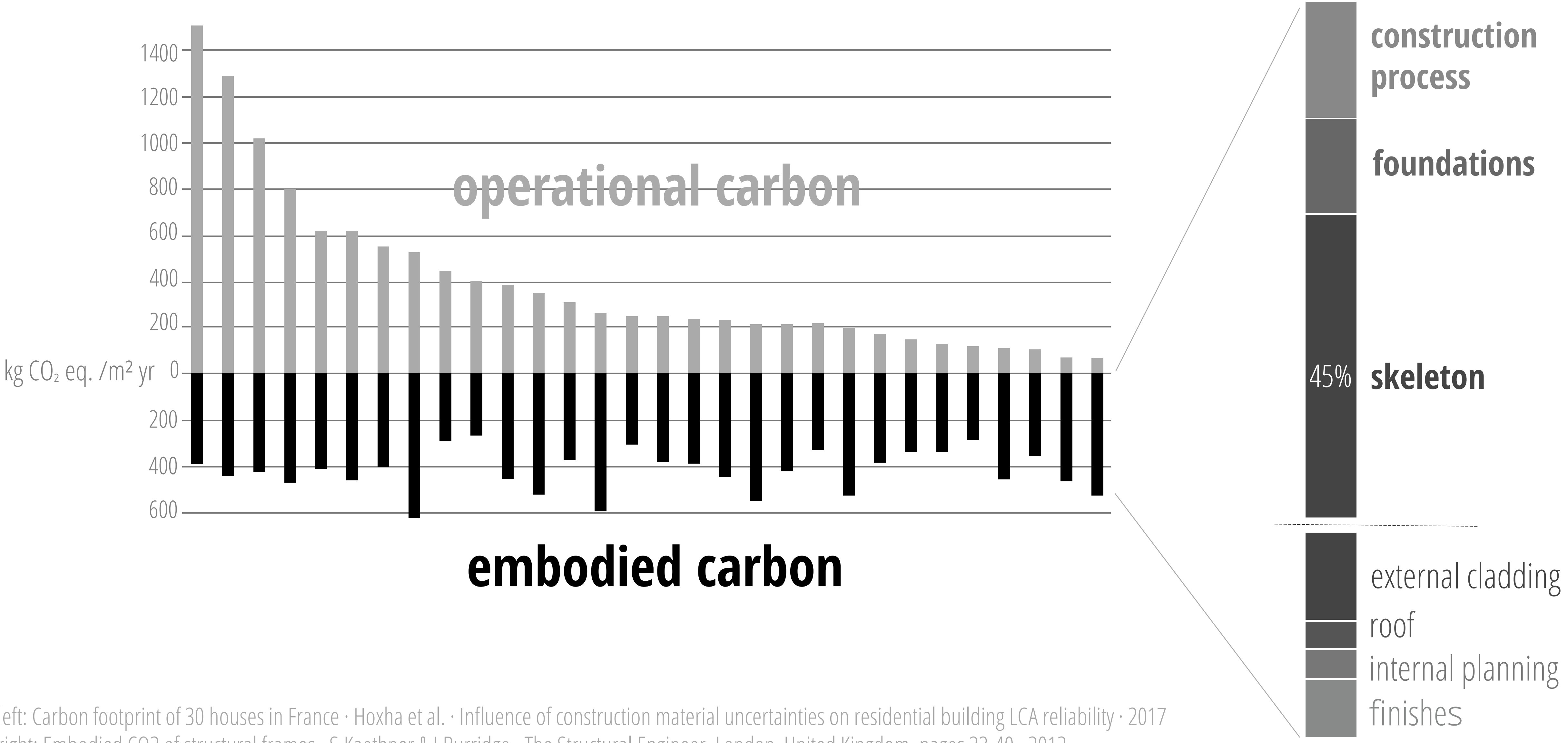




anthropogenic global CO_2 emissions

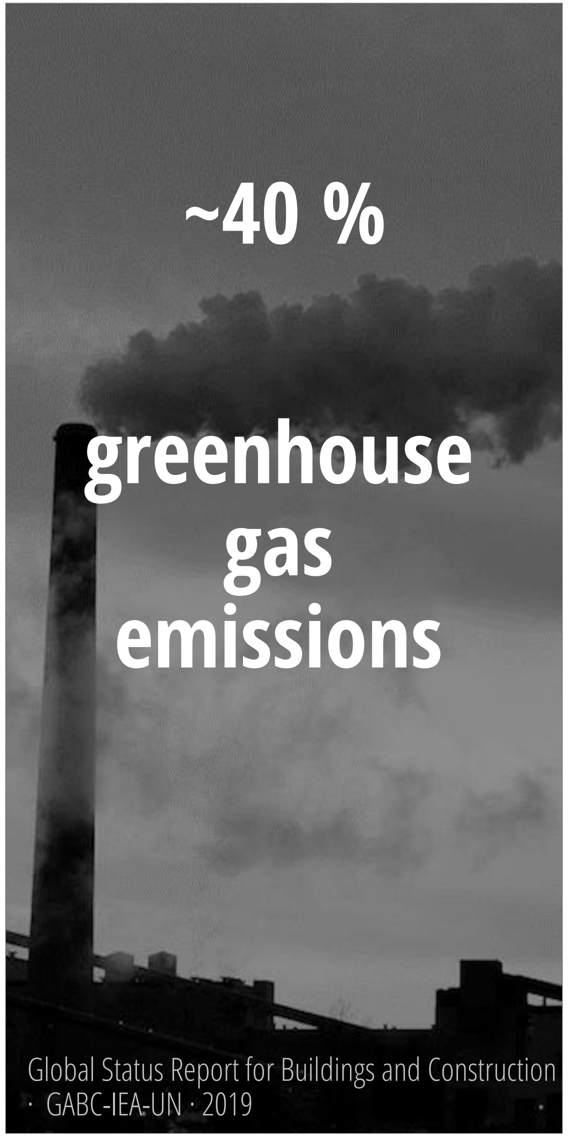


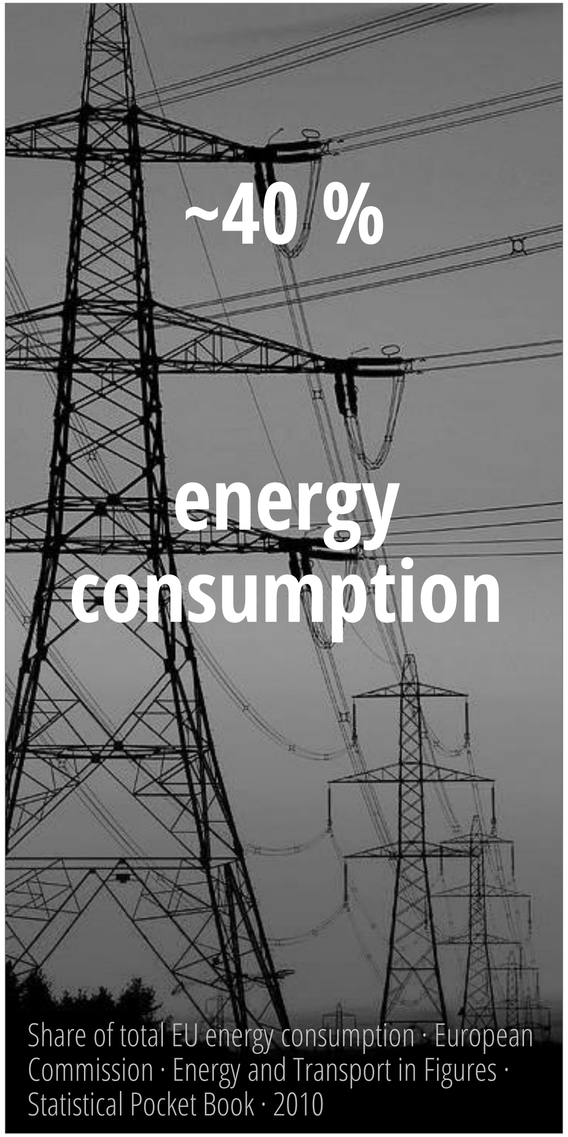
greenhouse gas emissions due to buildings

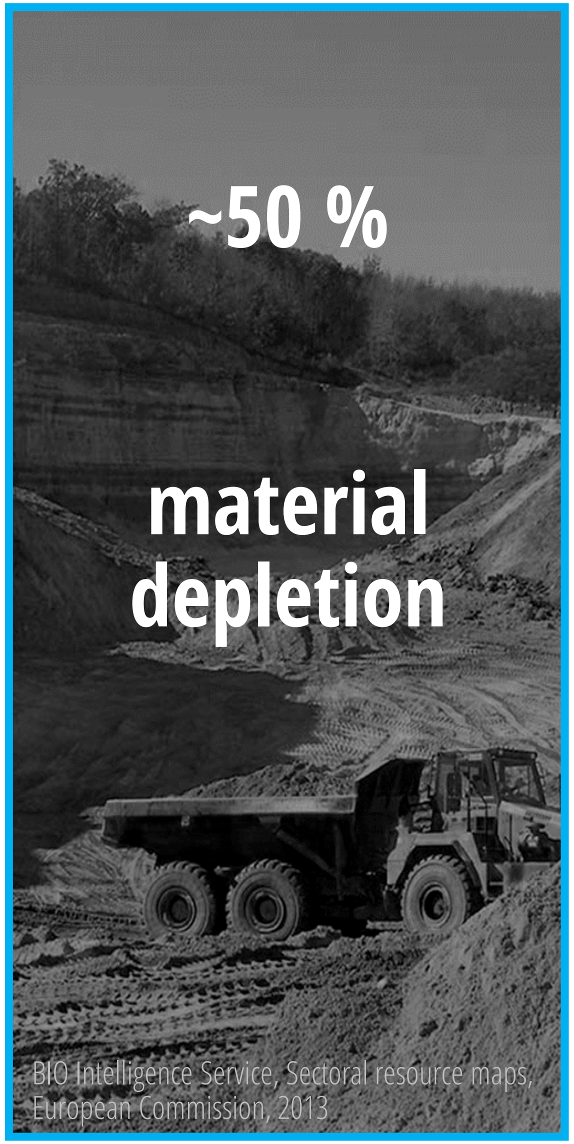


left: Carbon footprint of 30 houses in France · Hoxha et al. · Influence of construction material uncertainties on residential building LCA reliability · 2017
right: Embodied CO2 of structural frames · S.Kaethner & J.Burridge · The Structural Engineer, London, United Kingdom, pages 33-40 · 2012

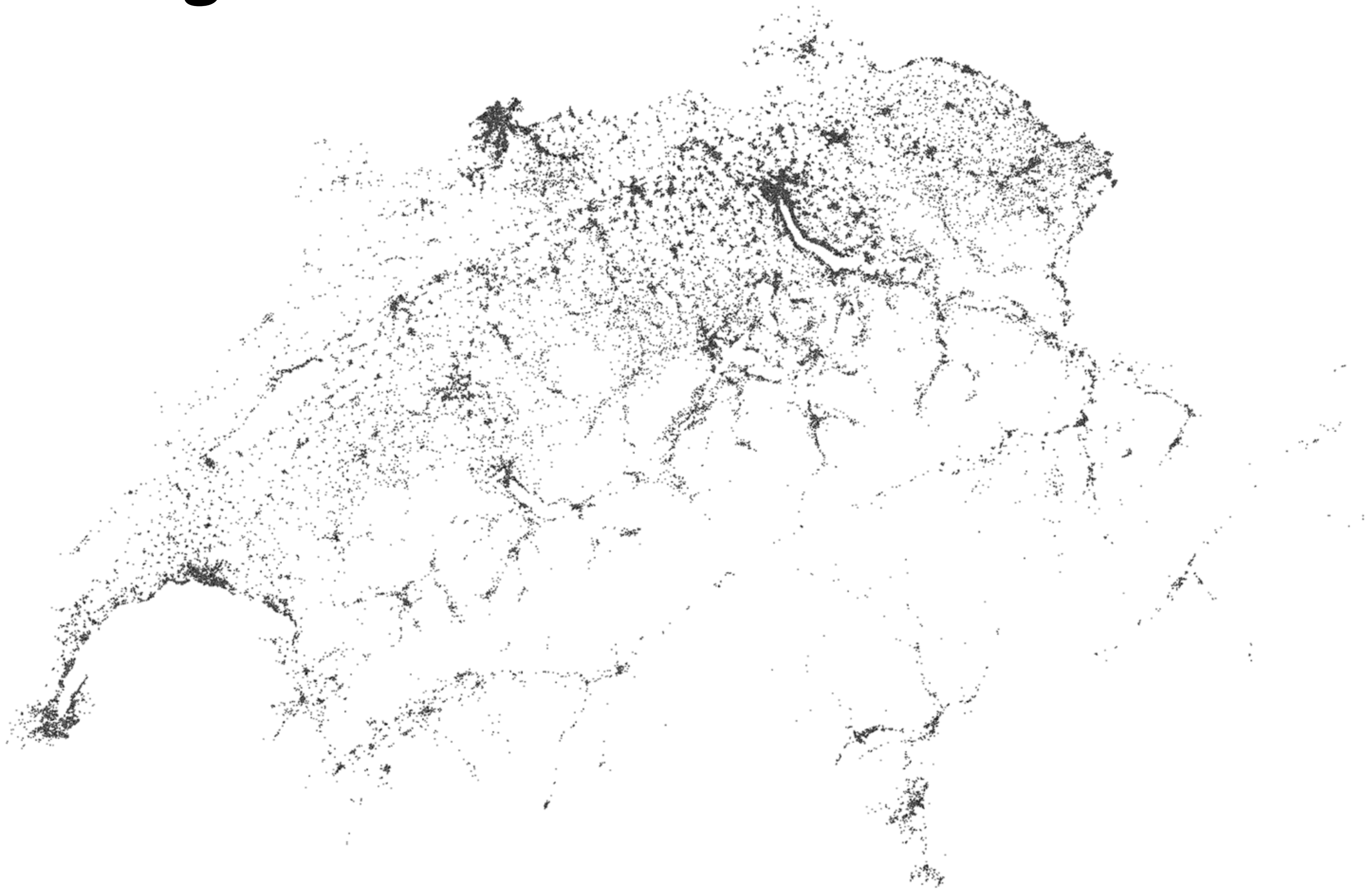
environmental toll of the built environment





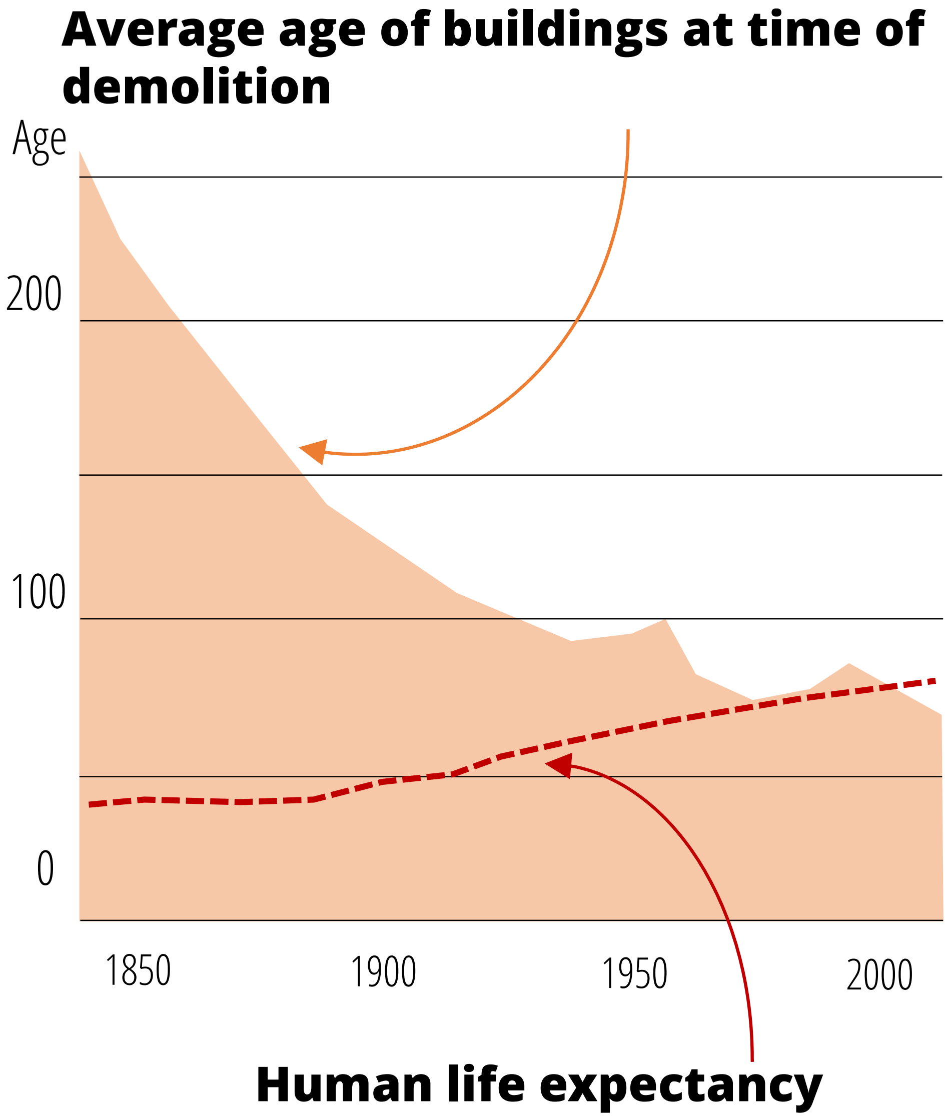


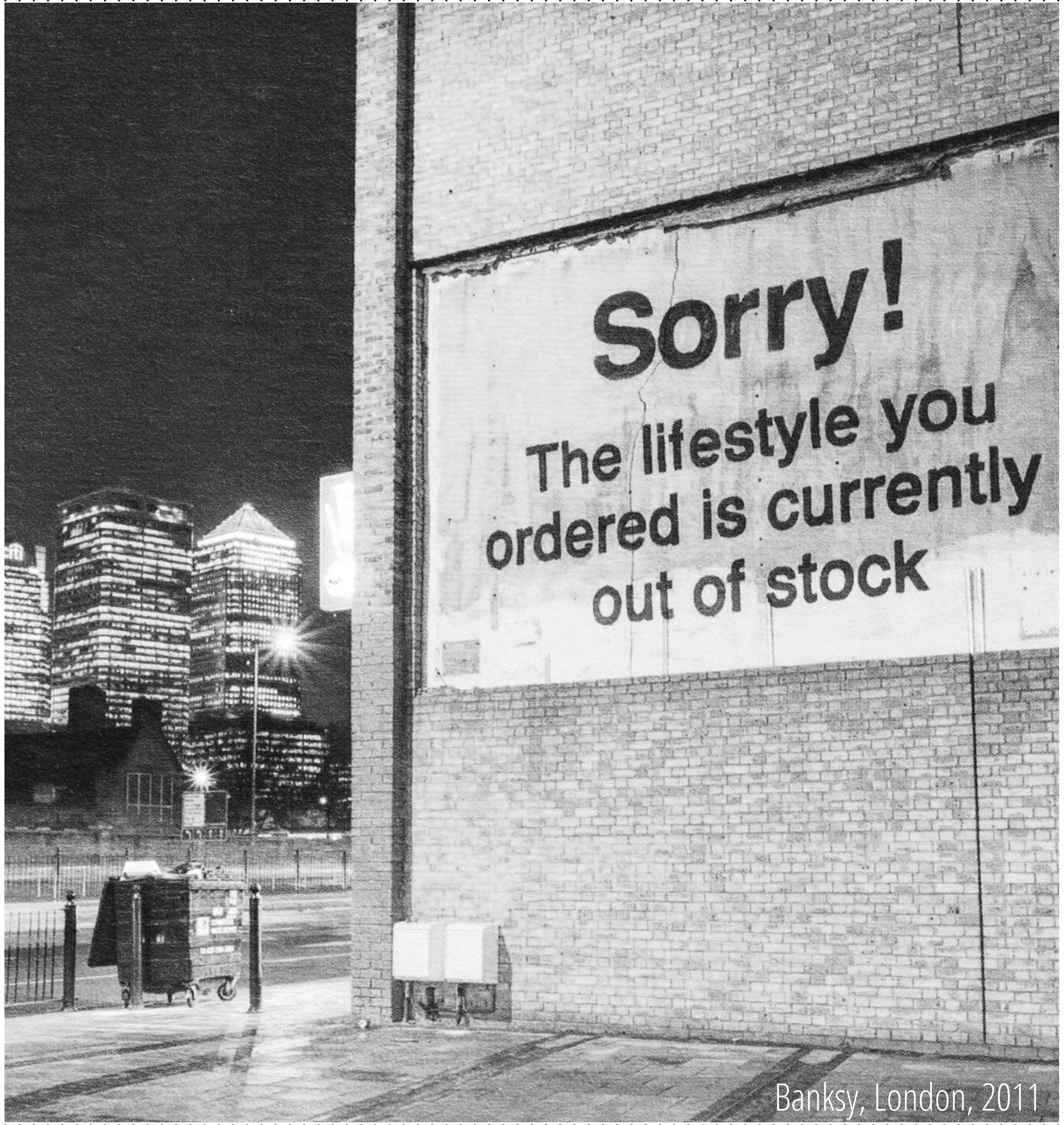
70,000 buildings demolished between 2000 and 2022



© Wegmann, EPFL, 2022

changing needs





Banksy, London, 2011

strategies

a matter of performance and design

$$\frac{\text{env. footprint}}{\text{lifespan}} = \frac{\text{env. footprint}}{\text{mass}} \times \frac{\text{mass}}{\text{use constraints}} \times \frac{\text{use constraints}}{\text{lifespan}}$$

product

↓ **low-carbon materials**

↓ **material-efficient systems**

↓ **versatile & reusable components**

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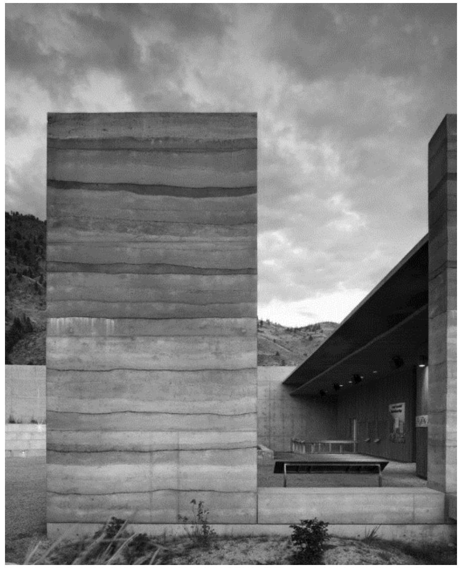
choice of materials

	$kgCO_2eq/kg$
aluminium	8.24
steel	1.77
glass	0.85
plywood	0.81
timber	0.46
bricks	0.22
reinforced concrete	0.15
marble	0.19
stone	0.06



conflicting objectives: example of a bar in tension

steel	timber	aluminum

conflicting objectives: example of a bar in tension

		steel	timber	aluminum
$\boldsymbol{\sigma}_{allow}$	[MPa]	200	7	130
$\boldsymbol{\rho}$	[kg/m^3]	8000	500	2700
EC	[kgCO_2eq/kg]	1.1	0.04	9

conflicting objectives: example of a bar in tension

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EC	[kgCO_2eq/kg]	1.1	0.04	9

carbon footprint [kgCO_2eq]

= **carbon coeff.** [kgCO_2eq/kg] **x mass** [kg]

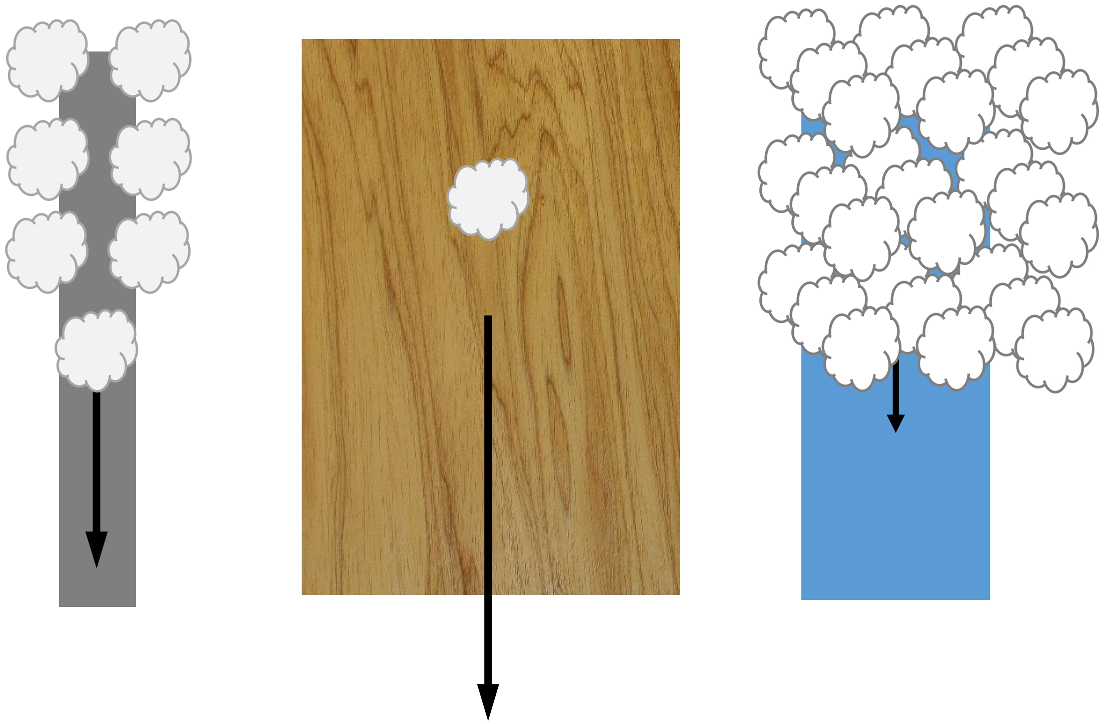
= $\boldsymbol{\rho}$ [kg/m^3] **x volume** [m^3]

= **length** [m] **x cross section** [m^2]

= **force** [kN] **x** $\boldsymbol{\sigma}_{allow}$ [kN/m^2]

conflicting objectives: example of a bar in tension

		steel	timber	aluminum
volume	[cm^3]	500	14285	770
mass	[kg/m^3]	4	7	2
EC	[$kgCO_2eq/kg$]	4.4	0.3	18



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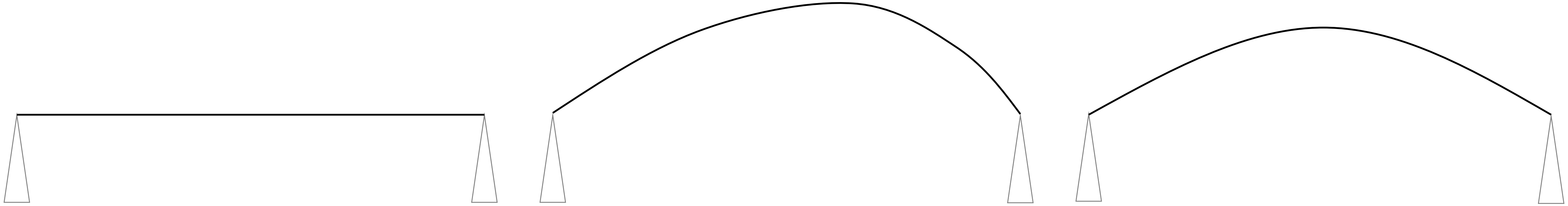
why form matters



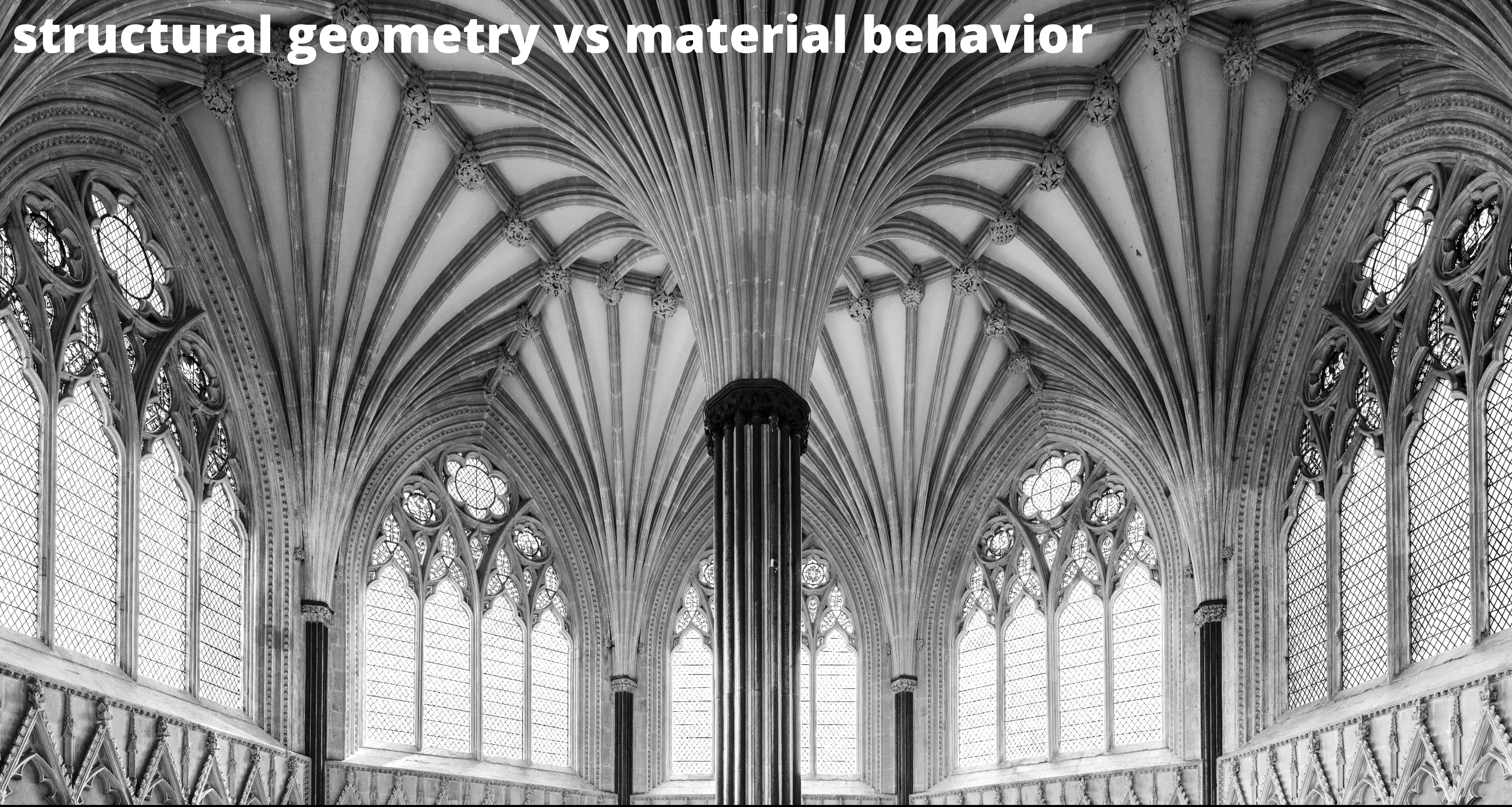
V = 0.75 V = 0.50 V = 0.25

› form matters!

structural geometry vs material behavior

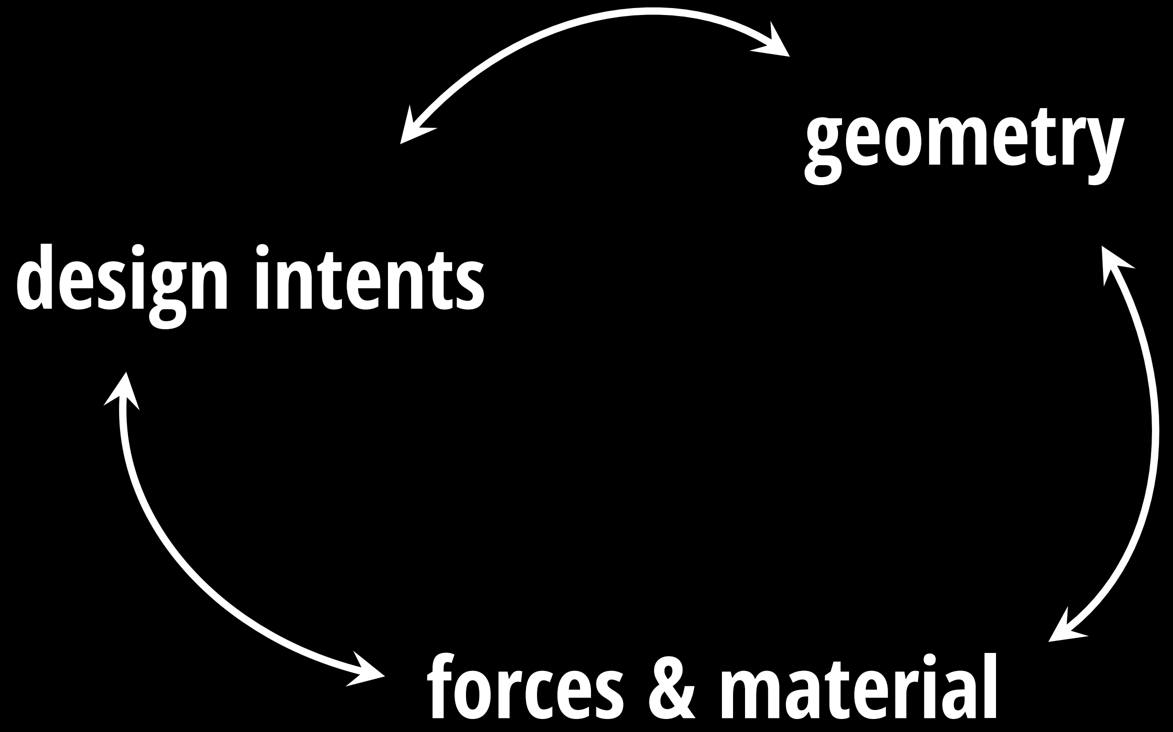
Temple d'Apollon, Corinthe, ca. 550BC.

structural geometry vs material behavior

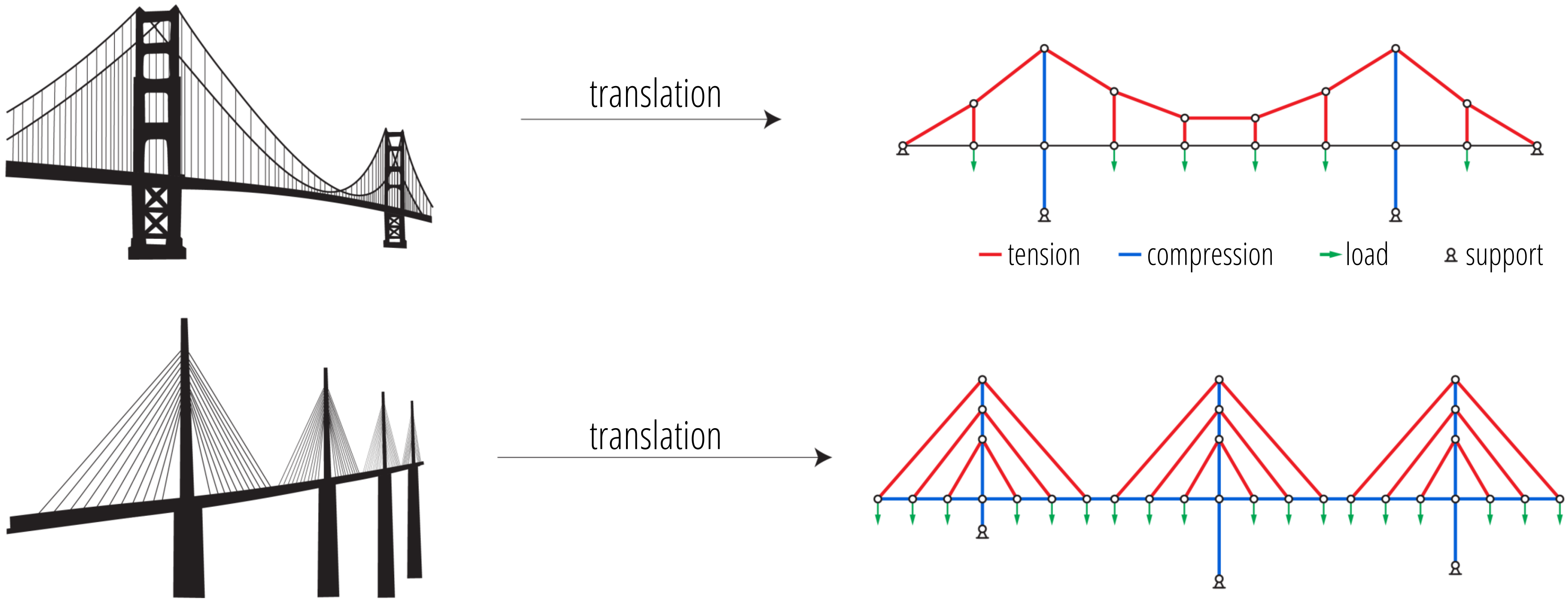


Chapter House – Wells Cathedral – 1310

structural design



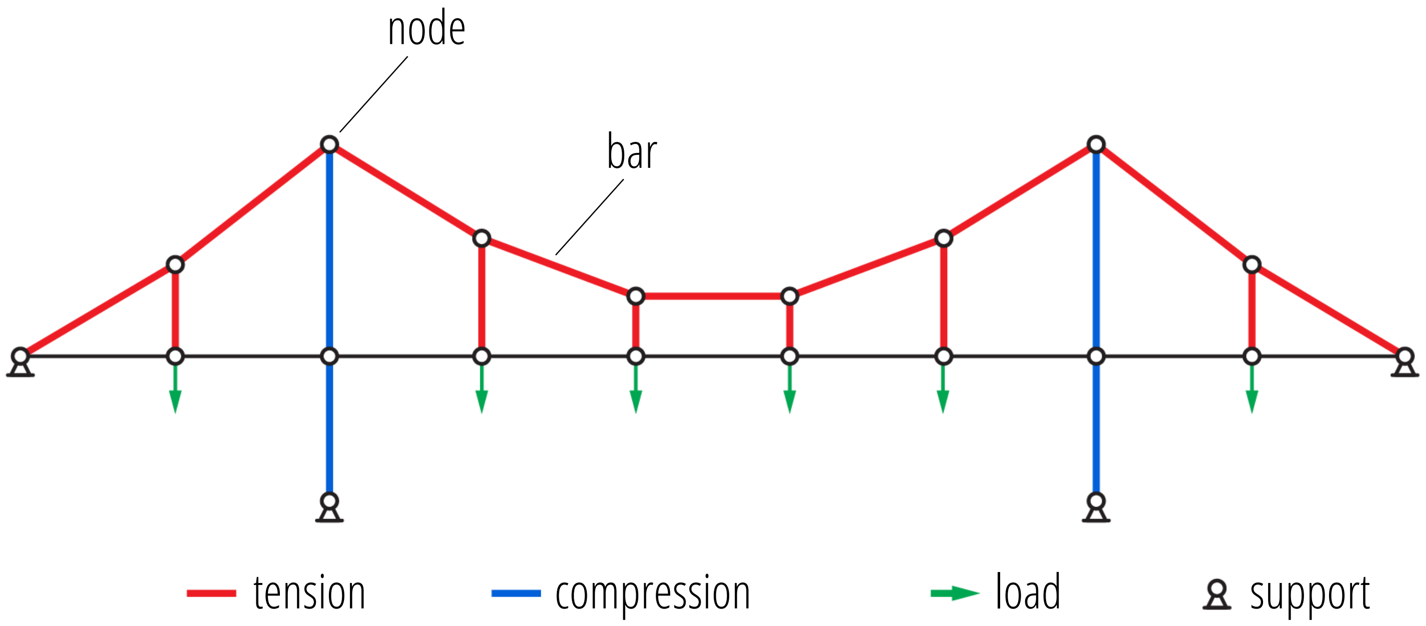
discrete equilibrium models



real structure

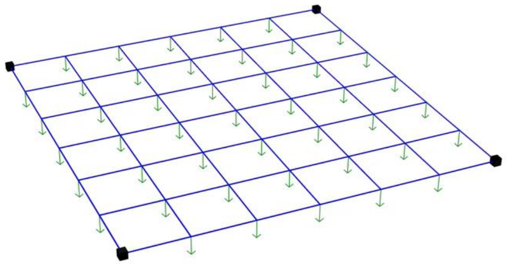
discrete equilibrium model

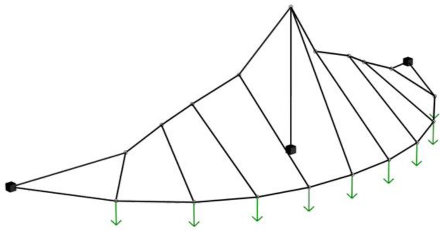
discrete equilibrium models (DEMs)

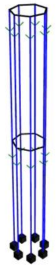


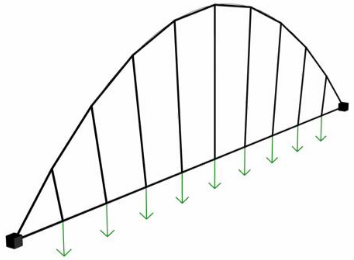
topology connectivity of the graph

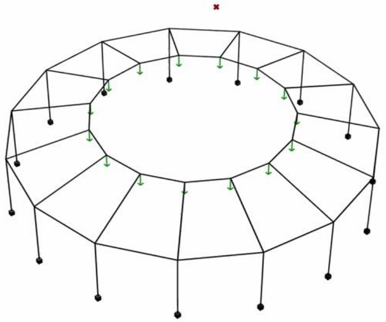
geometry position of the nodes











a matter of performance and design

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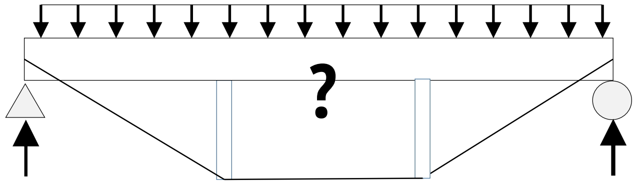


› **applied loads**

q = … kN/m (dead load, snow, wind,…)

› **static equilibrium**

$\sum H=0$

$\sum V=0$

$\sum M=0$

› **compatibility** (deformations & displacements)

› **stress limits**

σ ≤ …

› **serviceability limits**

δ ≤ …

› **cross sections**

A = …

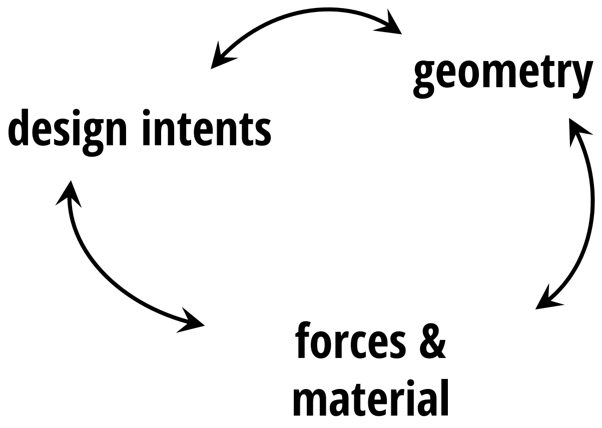
EI = …

› **construction**

› **environmental impact**

$$EI = \sum_{i=0}^{material} EC_i \times MASS_i$$

EC_i: $kgCO_2eq/kg$ — $MASS_i$: kg/unit



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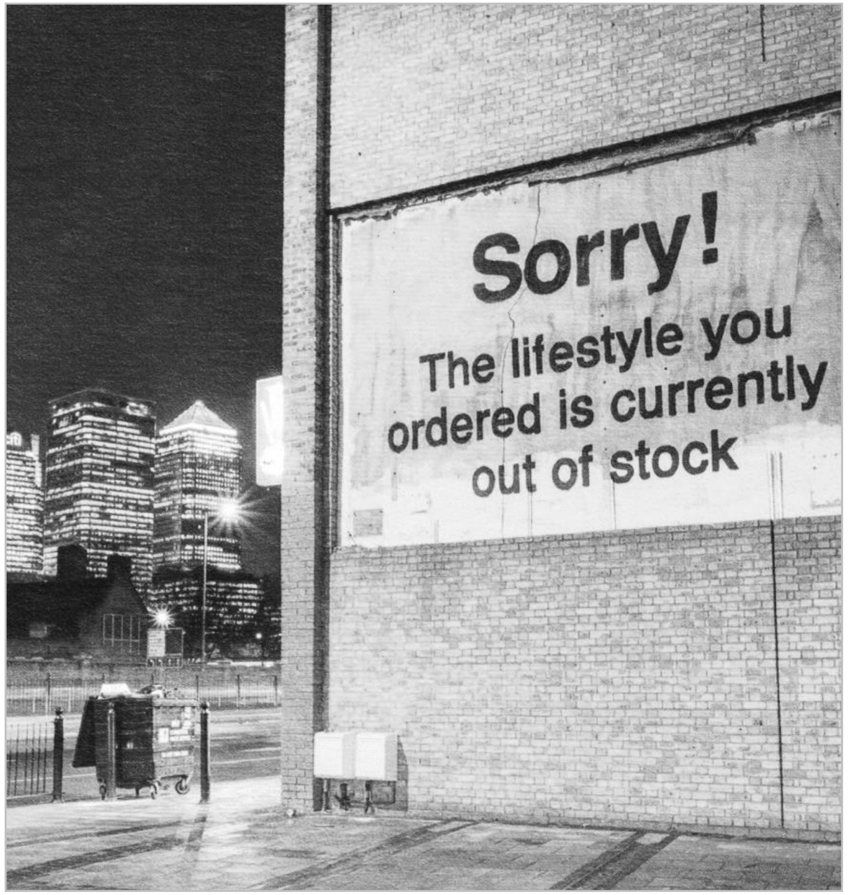
product

low-carbon materials

material-efficient systems

versatile & reusable components

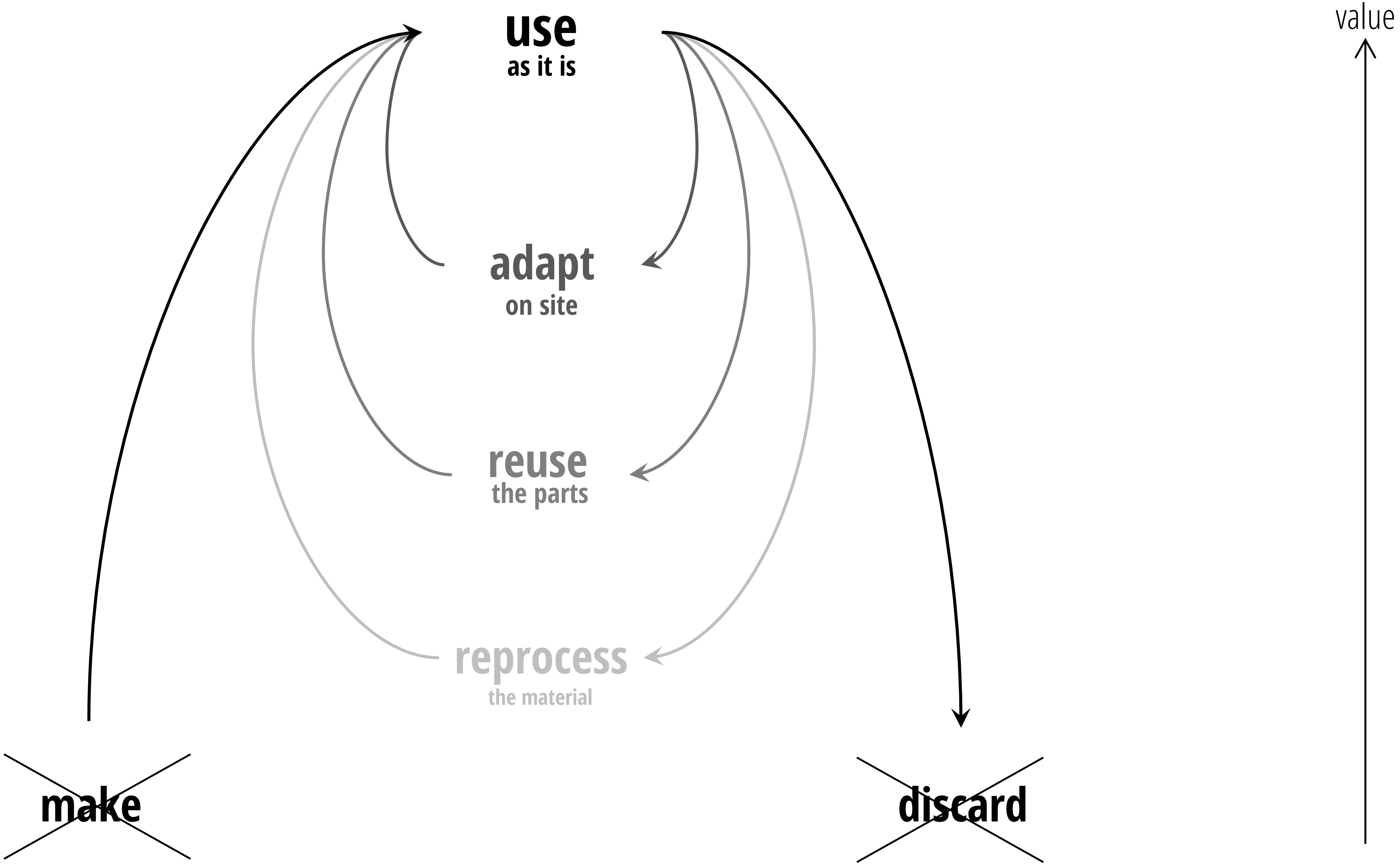
from linear to...



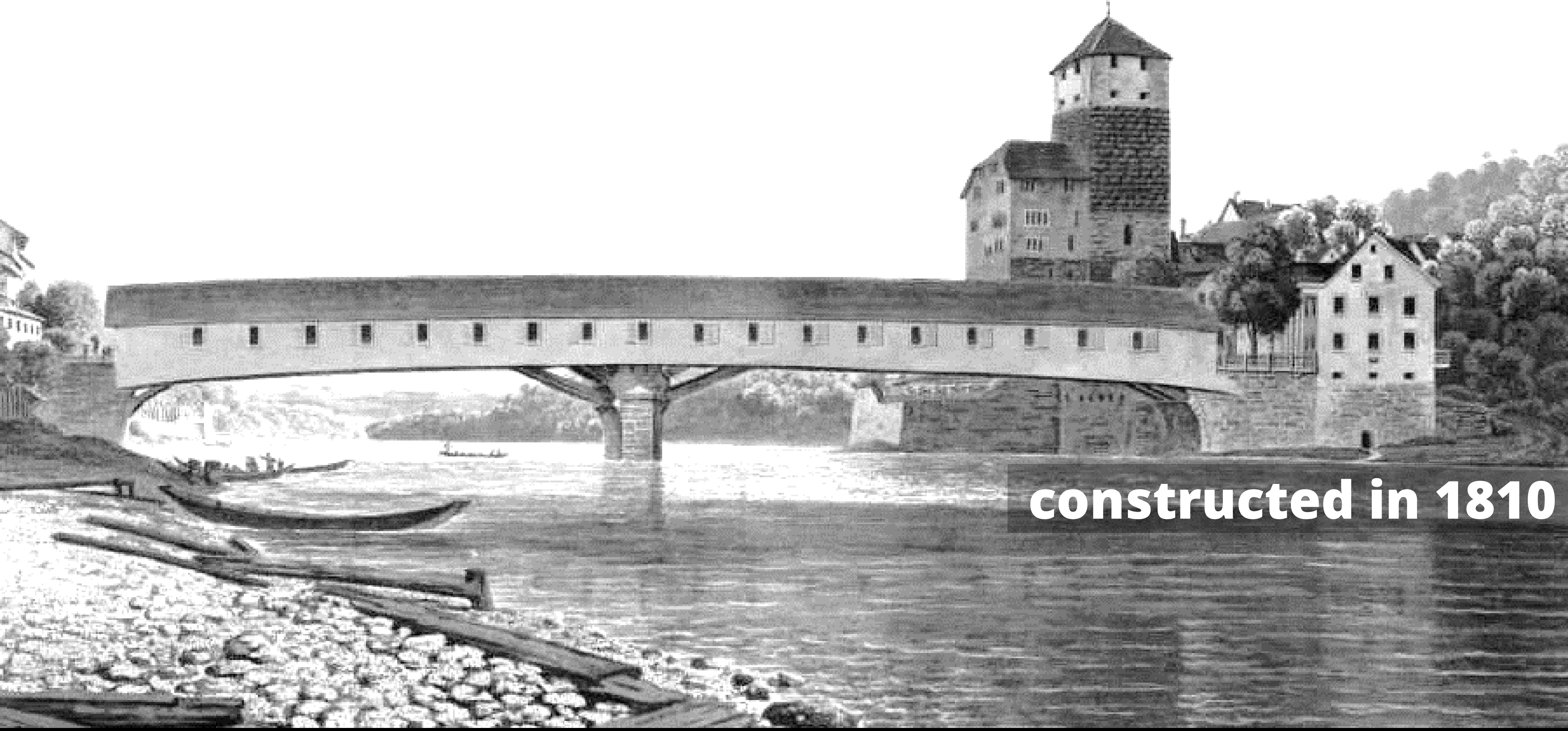
make → use → discard

circular economy

= maximize service life of existing products



Timber bridge – Eglisau, CH



constructed in 1810

Image: Zentralbibliothek Zürich; Fivet & Brütting, Nothing is lost, nothing is created, everything is reused, The Structural Engineer, 98(1), 2020

Image: Zentralbibliothek Zürich; Fivet & Brütting, Nothing is lost, nothing is created, everything is reused, The Structural Engineer, 98(1), 2020

Timber barn – Kloster Rheinau, CH

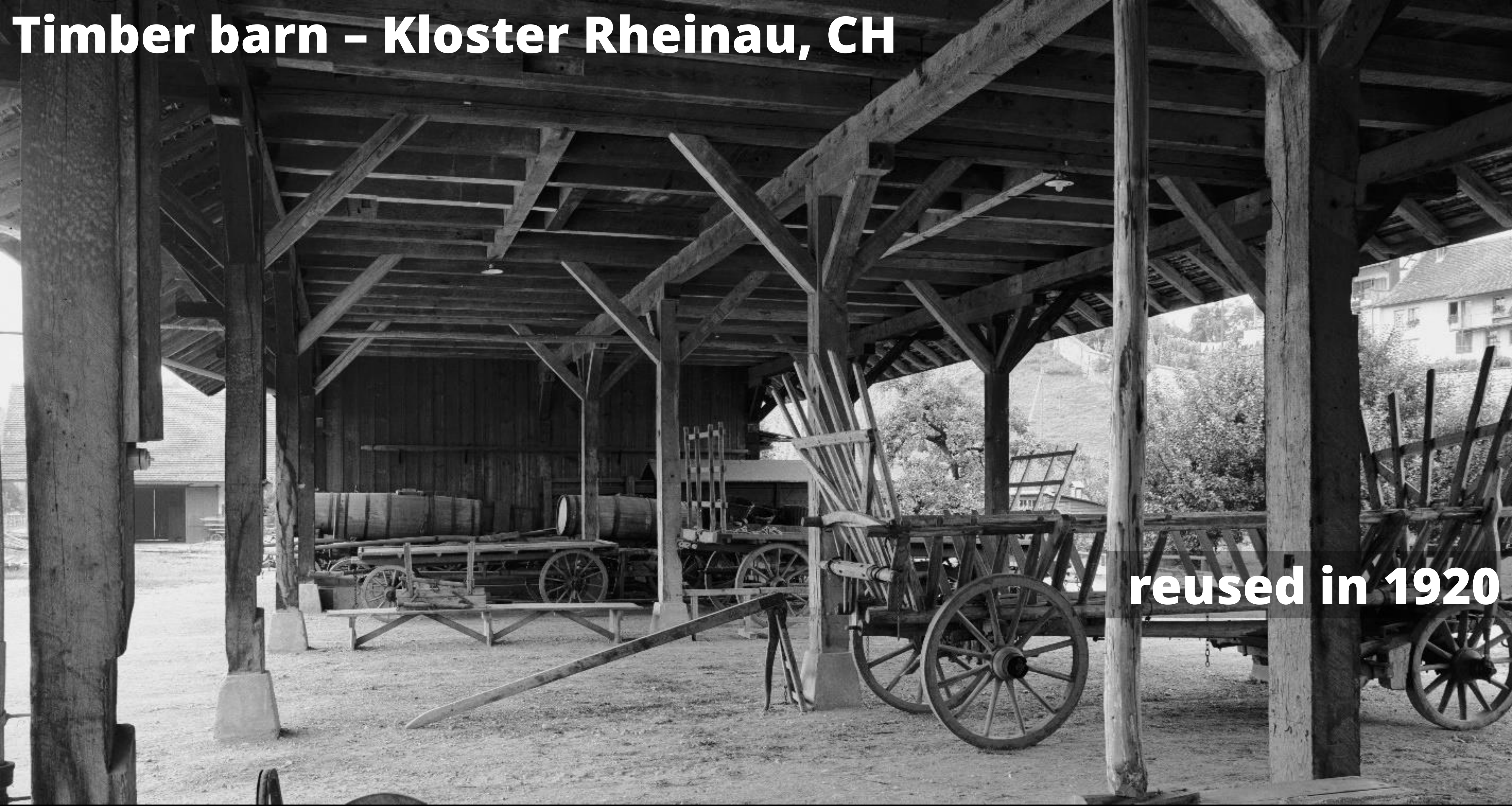


Image: Zentralbibliothek Zürich; Fivet & Brütting, Nothing is lost, nothing is created, everything is reused, The Structural Engineer, 98(1), 2020

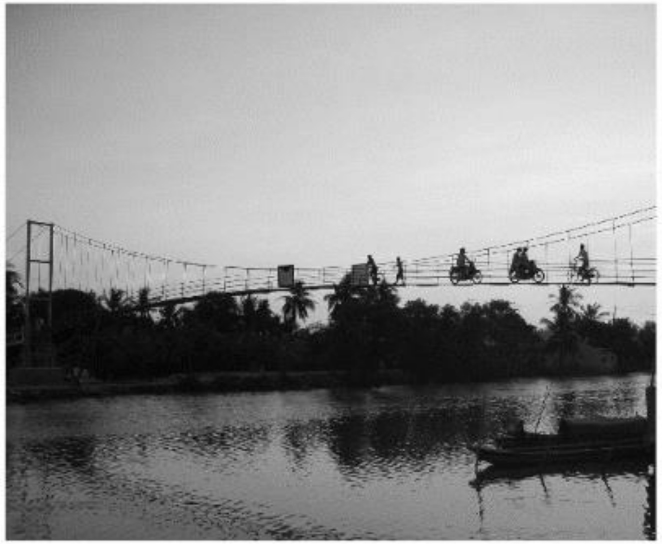
state 2022

Fivet & Brütting, Nothing is lost, nothing is created, everything is reused, The Structural Engineer, 98(1), 2020

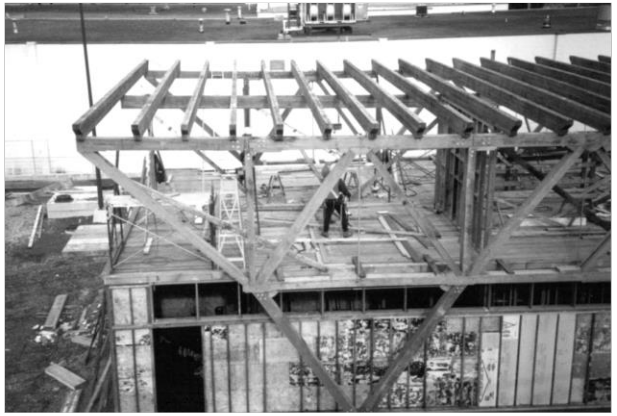
reuse was common in the past...

Rive's granary, Geneva, 1898 (photo by Boissonnas, Geneva main library)

...and it is today(?)



...and it is today(?)



Material Testing Facility 1999, Vancouver, Fast+Epp

...and it is today(?)

Olympic Stadium 2012, London, Buro Happold

Olympic Stadium, London (UK), 2012

Architects: Popolous
Engineers: Buro Happold

Reuse of second-hand gas pipeline tubes in the stadium roof truss.

Photo courtesy: Olympic Delivery Authority

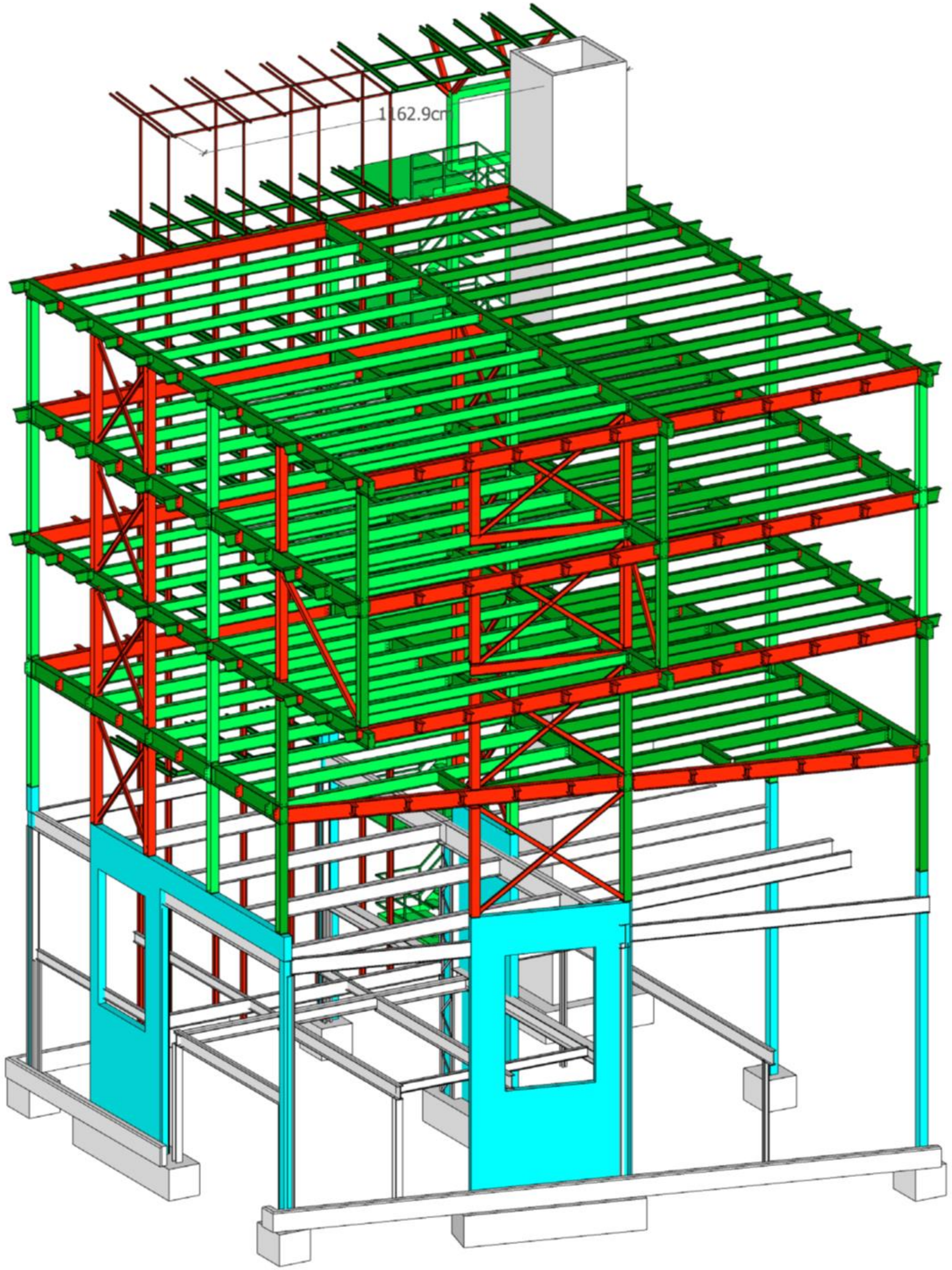
K118, Winterthur

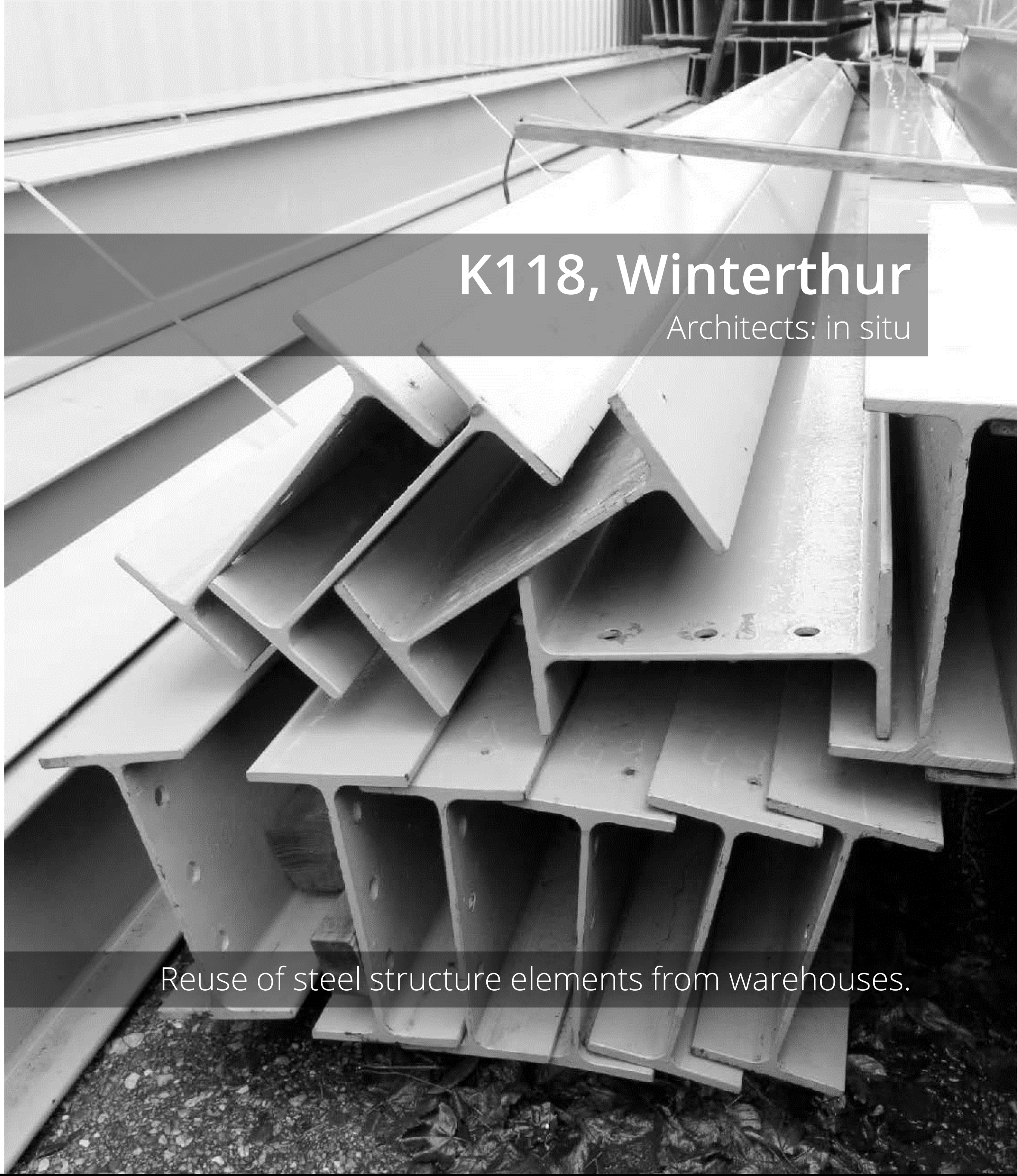
Architects: in situ

Reuse of steel structure elements from warehouses.

K118, Winterthur

Architects: in situ





K118, Winterthur

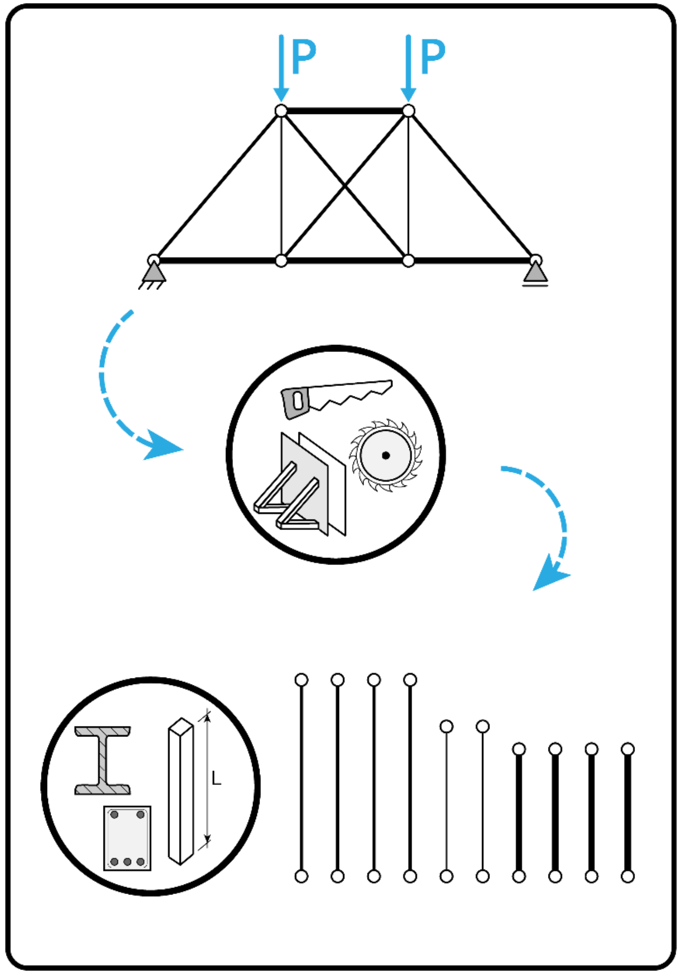
Architects: in situ

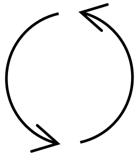
Reuse of steel structure elements from warehouses.

Image courtesy: in situ

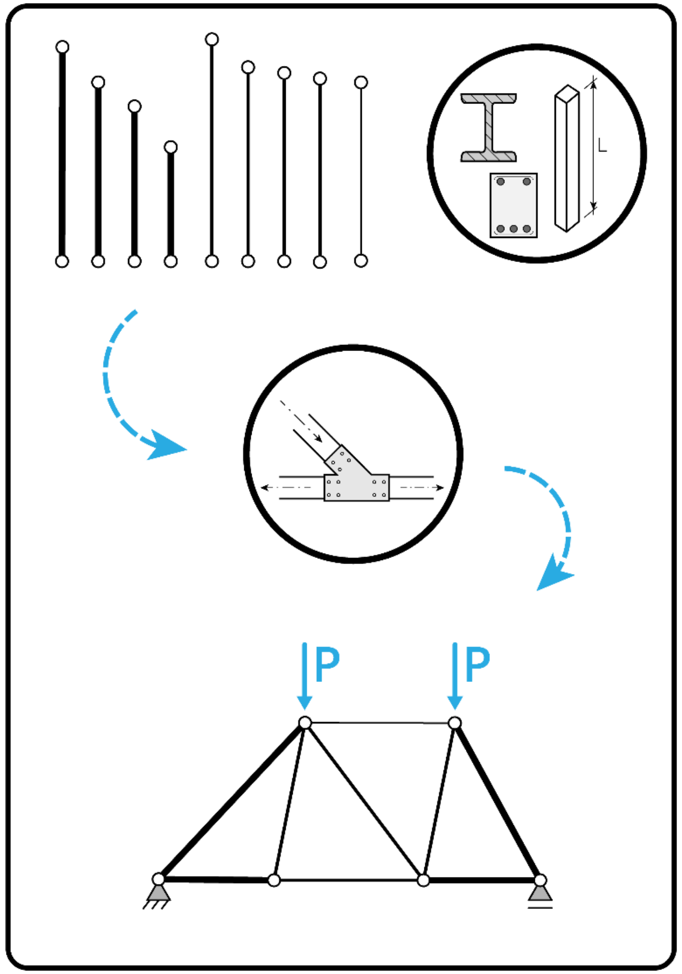
change of design paradigm

conventional design



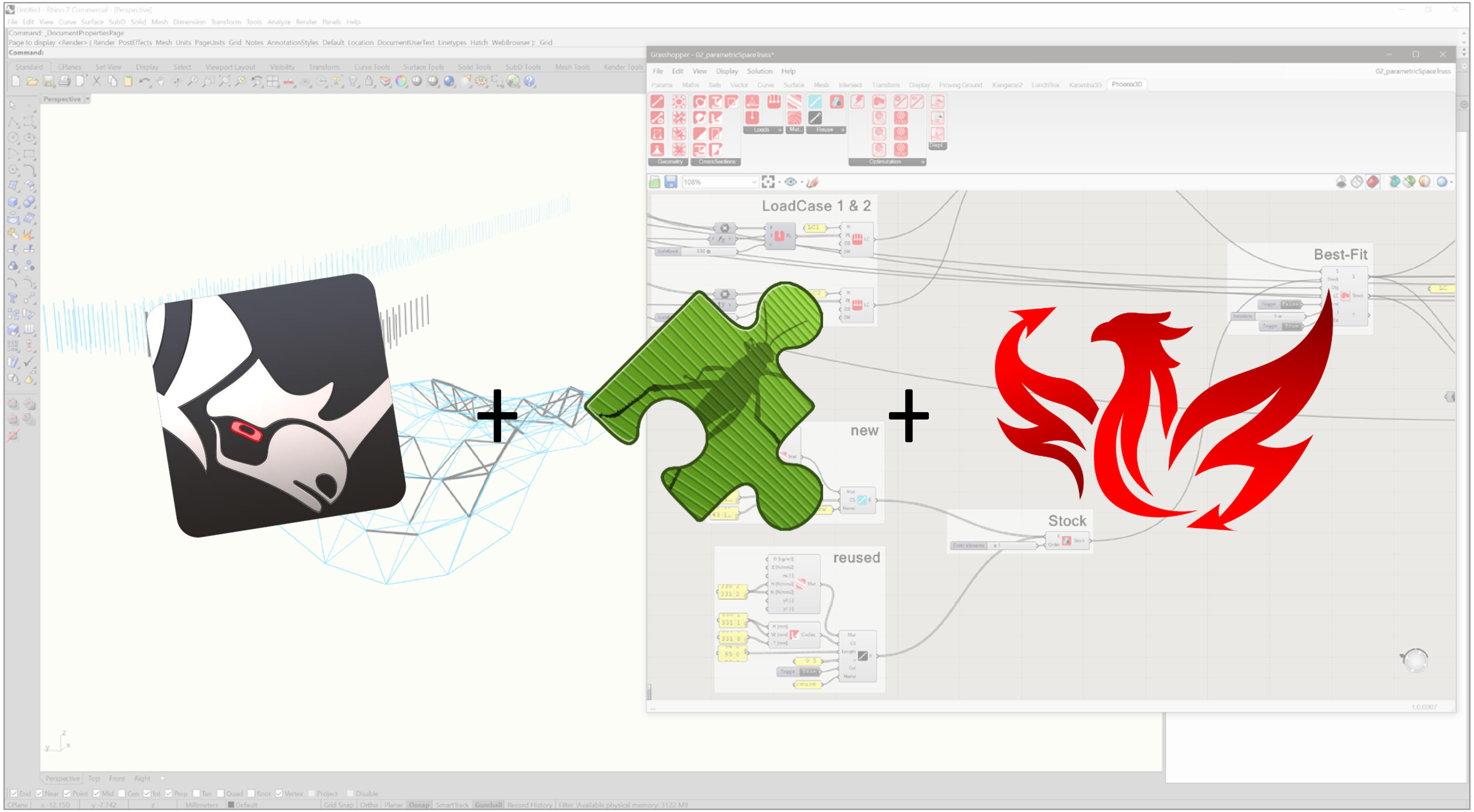


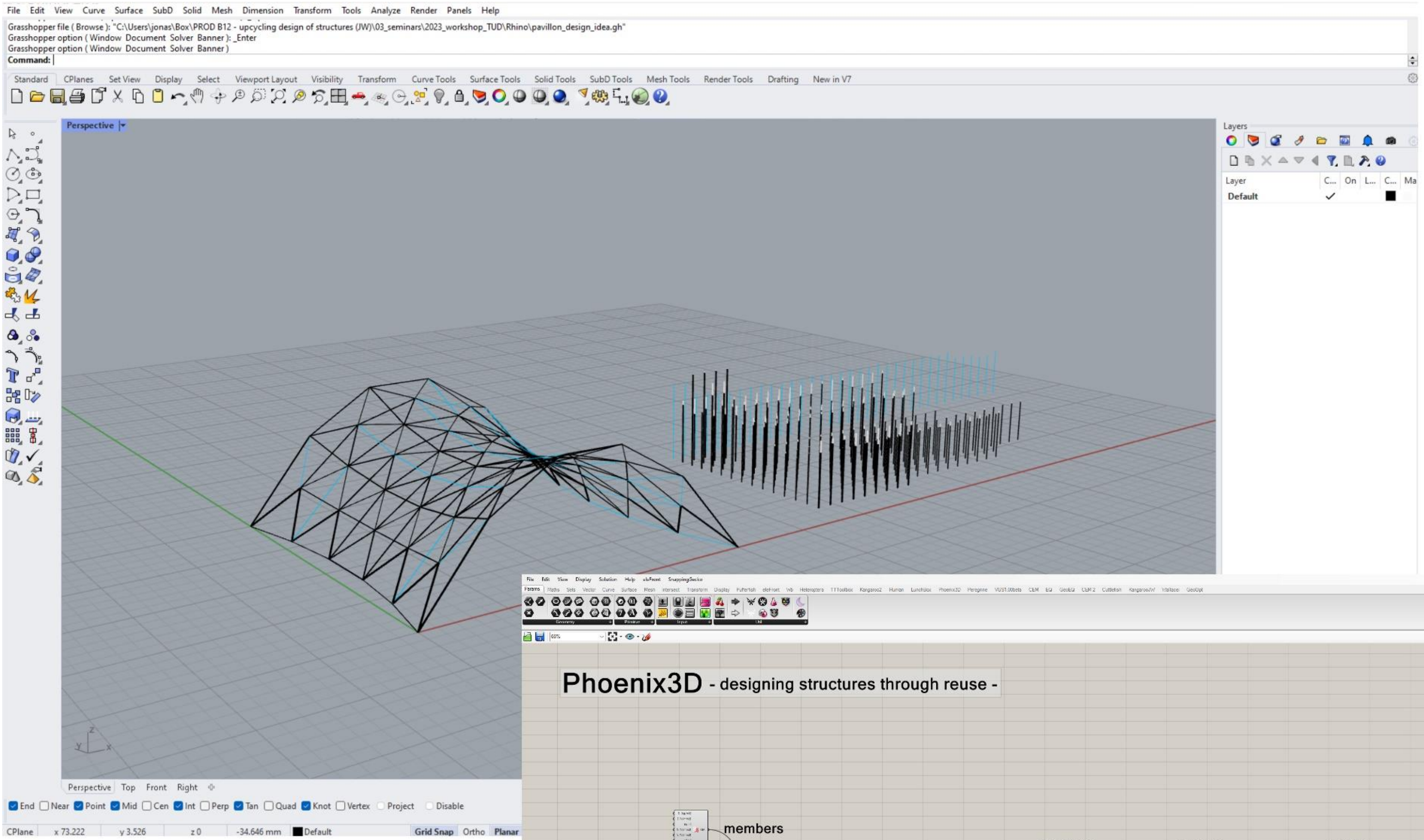
design through reuse

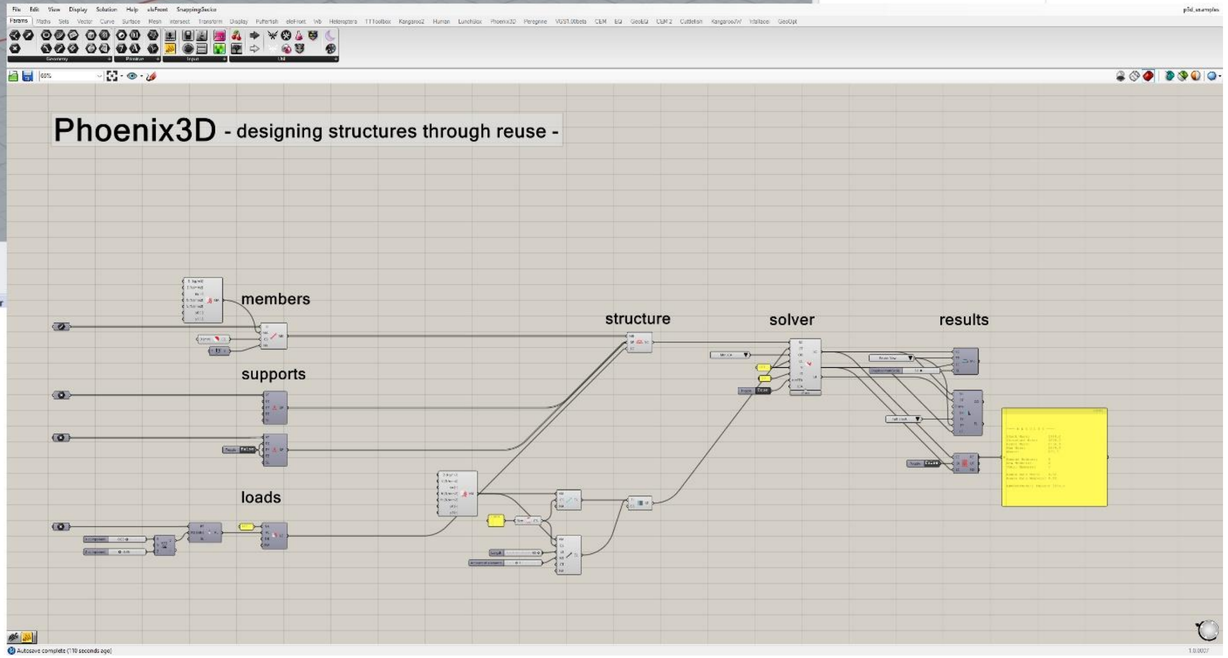


Brütting et al. 2019 · Design of Truss Structures through Reuse

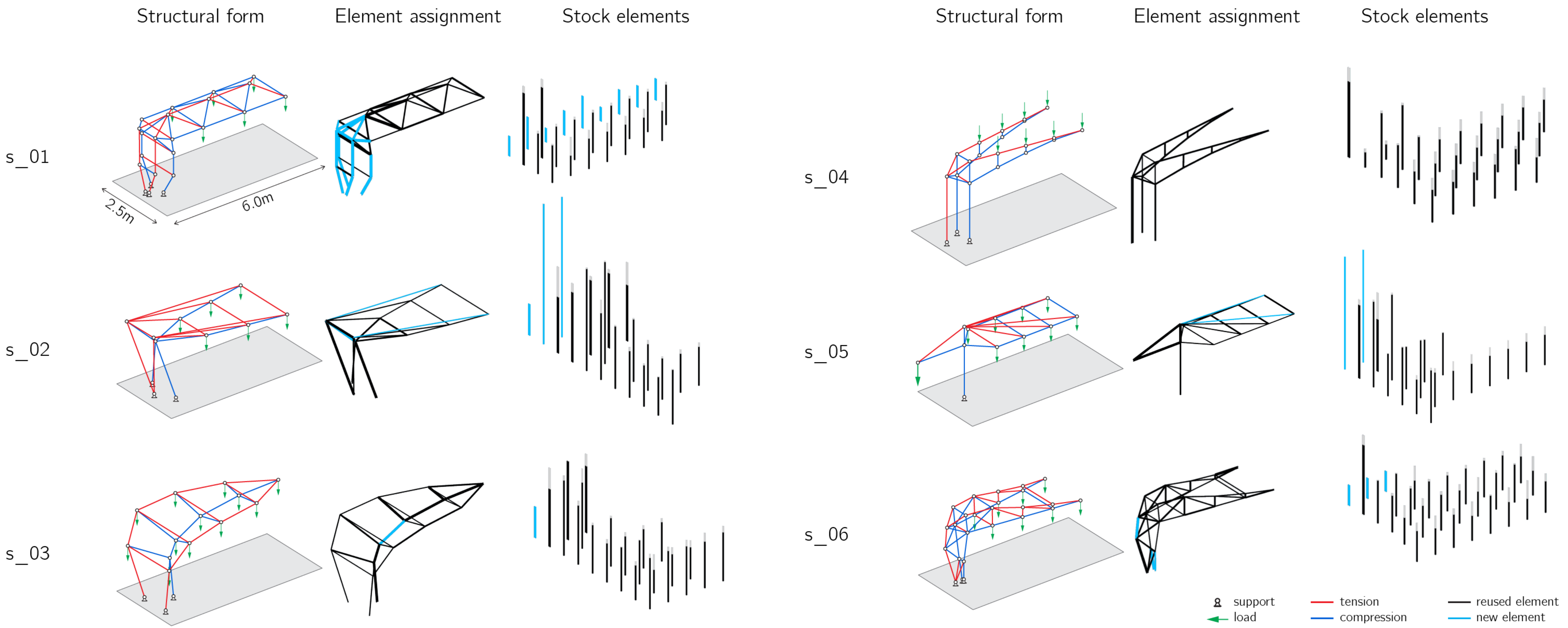
phoenix3d






Phoenix3D - designing structures through reuse -
members
supports
loads
structure
solver
results

efficiency + reuse: design of a bus station



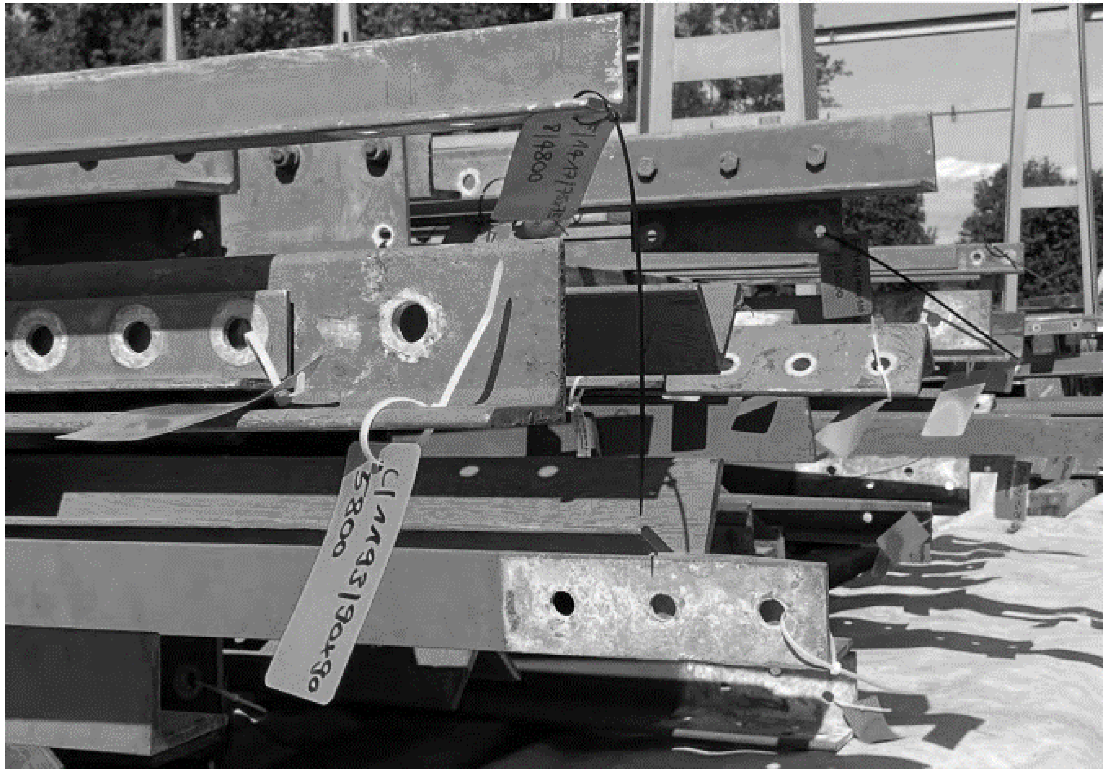
built project

Primeo Energie Lernwelt – Rapp Architekten

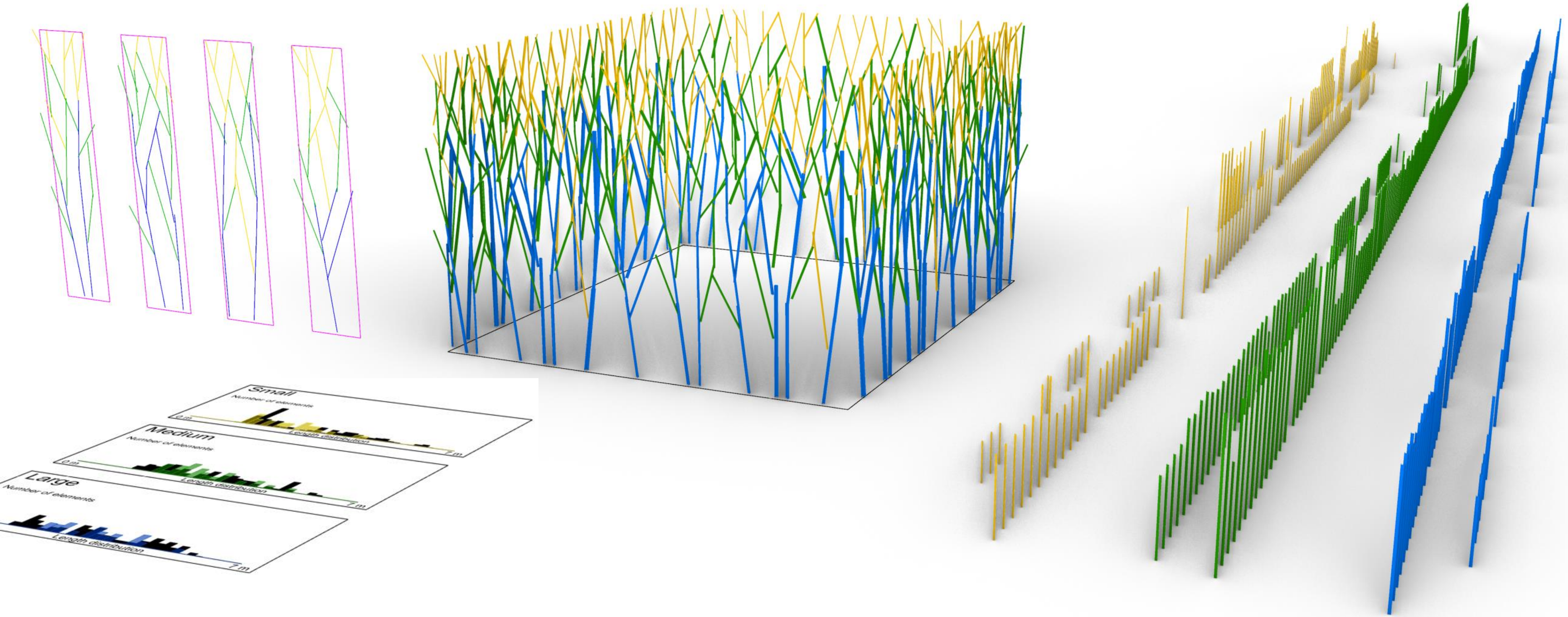
stock

baubüro in situ

swissgrid



design

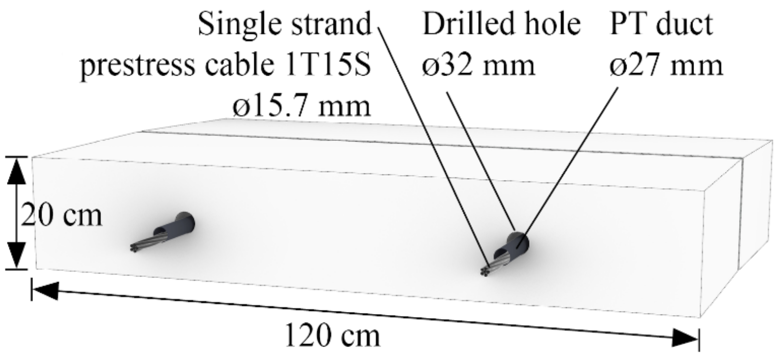

Small
Number of elements
0 m
Length distribution
7 m
Medium
Number of elements
0 m
Length distribution
7 m
Large
Number of elements
Length distribution
7 m


BIRSECK

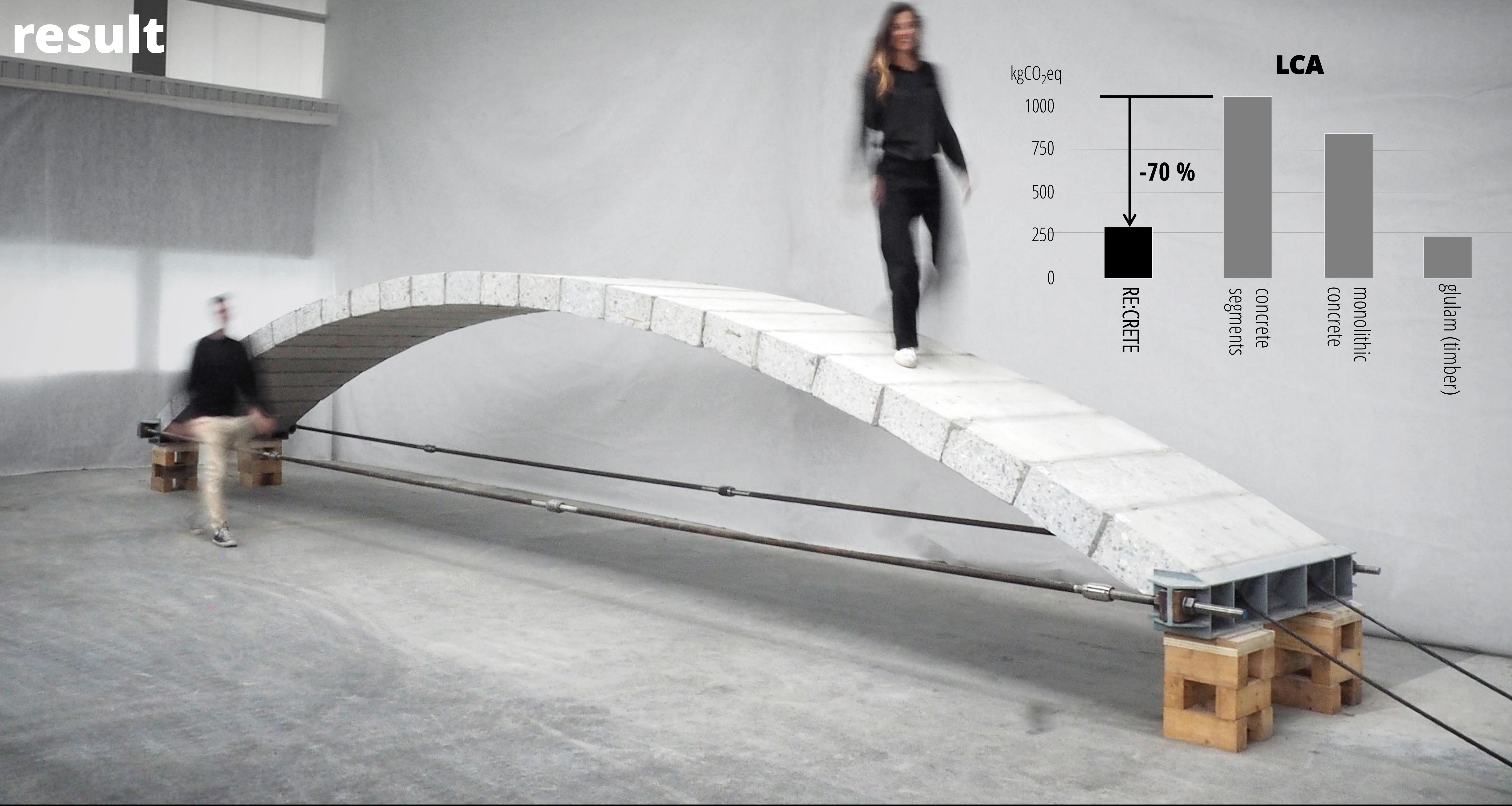
© Rapp Architekten

supply

assembly


Single strand
prestress cable 1T15S
ø15.7 mm
Drilled hole
ø32 mm
PT duct
ø27 mm
20 cm
120 cm

result


LCA
kgCO2eq
1000
750
500
250
0
-70 %
RE:CRETE
concrete segments
monolithic concrete
glulam (timber)

pre-dimensioning

pre-sizing: typical slenderness

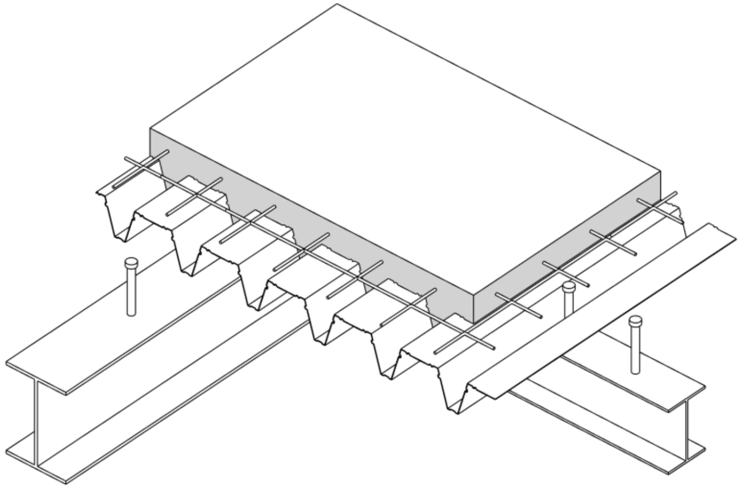
Material	Structure	economic design l/h of a simple beam
steel	Vierendeel	7 – 10
	truss	10 - 15
	spatial truss	12 - 18
	beam	**15 - 20**
reinforced concrete	**beam**	**12 - 18**
	slab	**20 - 25**
pre-cast concrete	**beam**	**18 - 25**
	slab	**28 - 35**
timber	**beam**	**15 - 20**

massive timber beams

glulam beams

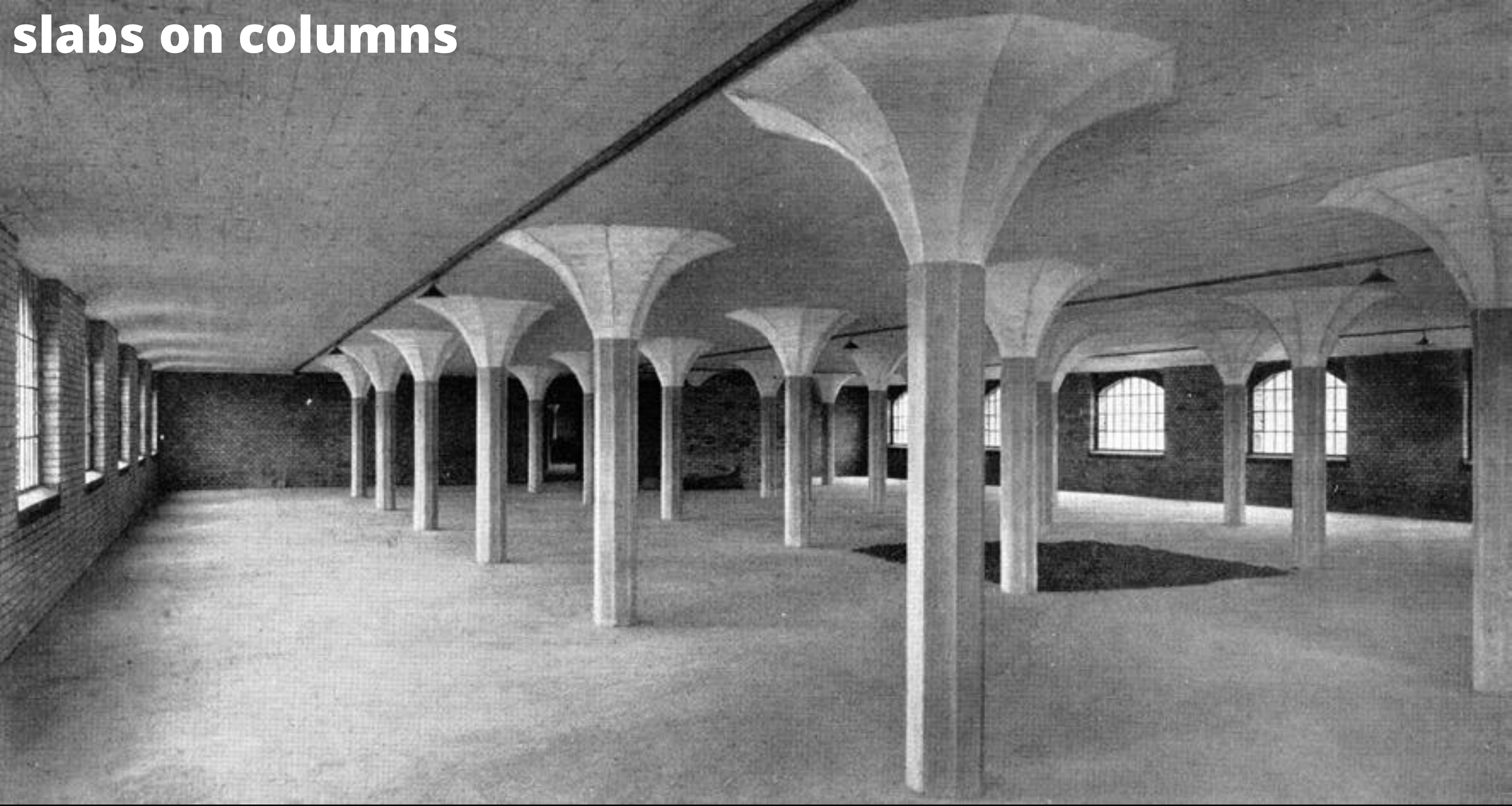
Cité du temps, Arch. Shigeru Ban, Ing. SJB.Kempter.Fitze AG, Bienne, 2014

mixed floor



slabs on beams

slabs on columns



Giesshubel Warehouse, Ing. Robert Maillart, Zurich – Suisse, 1910

pre-sizing of reinforced concrete slabs

slab system	typical span L (economic)	recommended slenderness h/L
slab on walls	8 m	1/25 to 1/35
slab on columns	6 – 9 m	1/20 to 1/30
slab on (mushroom) columns or with additional depths	6 – 15 m	1/25 to 1/35 (h_{min} = 200 mm)
slab on beams	6 – 15 m	1/25 to 1/35
ribbed slab - standard - prefabricated and pre-stressed	 7 – 12 m < 18 m	 Total : 1/20 to 1/35 spacing of ribs < 2h
cassette slab	12 – 20 m	ribs : 1/15 to 1/20 slab : h_{min} = 120 mm
cantilevered slab	2 – 3 m	1/10

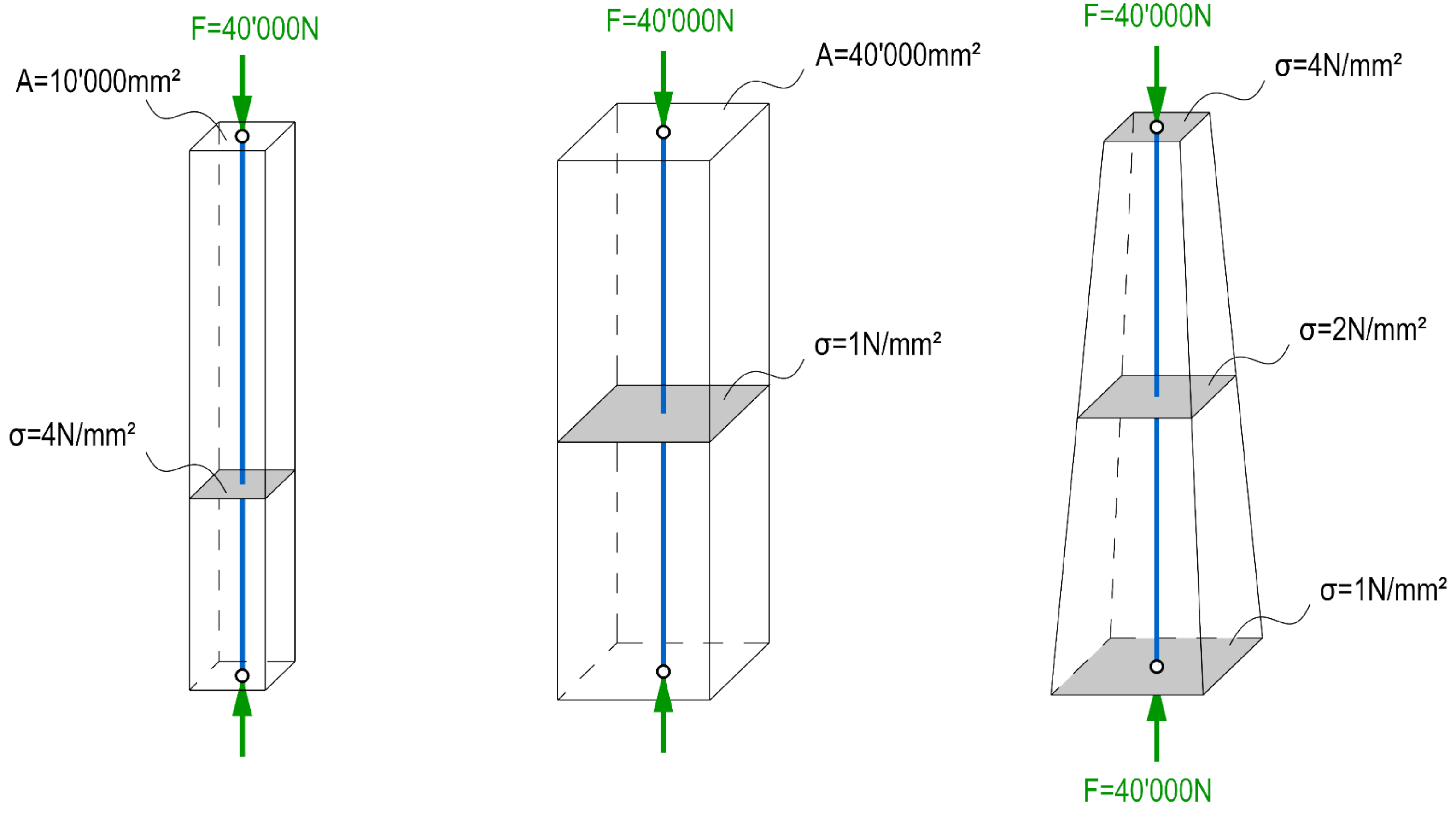
pre-sizing of columns

σ = F/A [N/mm²]

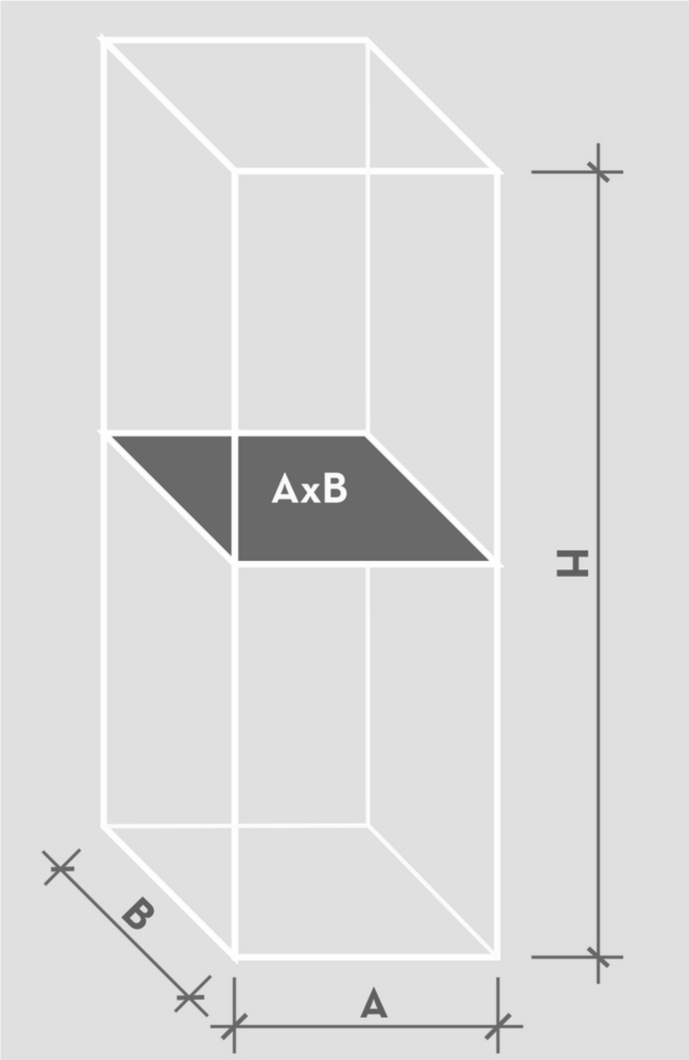
σ ("sigma") = constraint
F = axial force applied to cross-section
A = considered cross-section

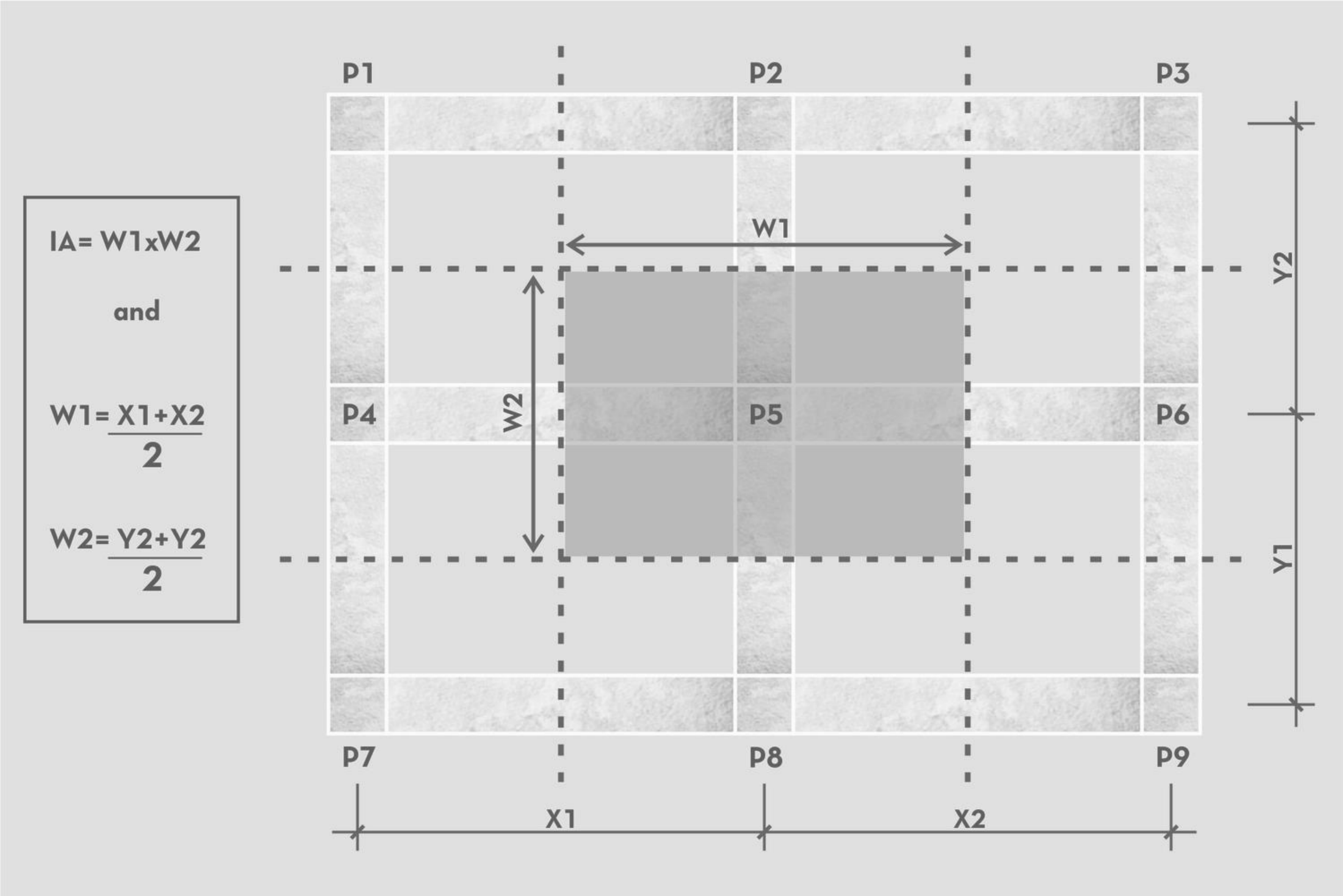
1N/mm² = 1'000'000Pa = 1MPa

+ stability check
(buckling)



pre-dimensioning of column spacing

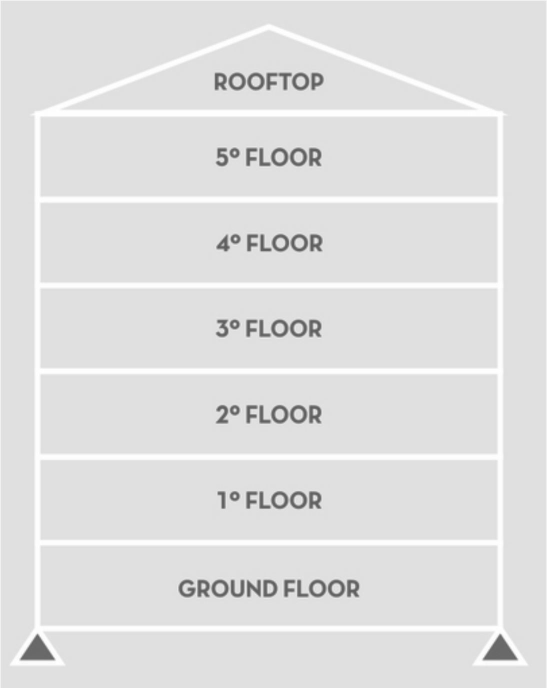




pre-sizing of concrete columns

assumptions:

- **load**
  10 kN/m^2
- **resistance**
  10 MPa or N/mm^2
- Min 200x200 mm



Étage	Aire d'influence	Charge	Charge accumulée	Aire poteau	Dimensions
	m^2	kN	kN	mm^2	mm
Rooftop	40	200			
5	40	400	200	20000	200x200
4	40	400	600	60000	200x300
3	40	400	1000	100000	350x350
2	40	400	1400	140000	300x500
1	40	400	1800	180000	400X500
0	40	200	2200	220000	450x450
Fondation			2400	240000	

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pre-sizing of foundations

$$\text{Area foundation} = \frac{\text{load}_{\text{building}}}{\text{capacity}_{\text{sol}}}$$

$$\text{dim foundation} = \frac{\text{Area foundation}}{\text{\# fondations}}$$

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pre-sizing of foundations

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Étage	Aire d'influence	Charge	Charge accumulée	Aire poteau	Dimensions
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3	40	400	1000	100000	350x350
2	40	400	1400	140000	300x500
1	40	400	1800	180000	400X500
0	40	200	2200	220000	450x450
Fondation			2400	240000	

pre-sizing of foundations

$$\text{Area foundation} = \frac{\text{load}_{\text{building}}}{\text{capacity}_{\text{sol}}}$$

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Type of Soil	Bearing capacity kN/m2
Cohesive Soils	
Soft shale, hard or stiff clay in a deep bed, dry state	440
Medium clay readily indented with a thumbnail	245
Moist clay and Sand clay mixture which can be indented by thumb pressure	150
Black cotton soil/expansive clay (50% saturated) in dry state	130 to 160
Soft clay indented with moderate thumb pressure	100
Very soft clay which can be penetrated with the thump up to few centimetres	50
Cohesionless Soil	
Compact gravel/sand and gravel mixture with good resistance against penetration of tools	440
Compact and dry coarse sand	440
Compact and dry medium sand	245
Loose gravel or sandy gravel mixture, dry state	245
Fine sand and silt (consists of dry lumps)	150
Loose and dry fine sand	100
Rocks	
Hard rocks such as granite trap, diorite etc.	3240
Laminated rocks such as sandstone, limestone, etc.	1620
Residual deposits of shattered and broken bedrock and hard shale, cemented material	880
Soft rocks	440

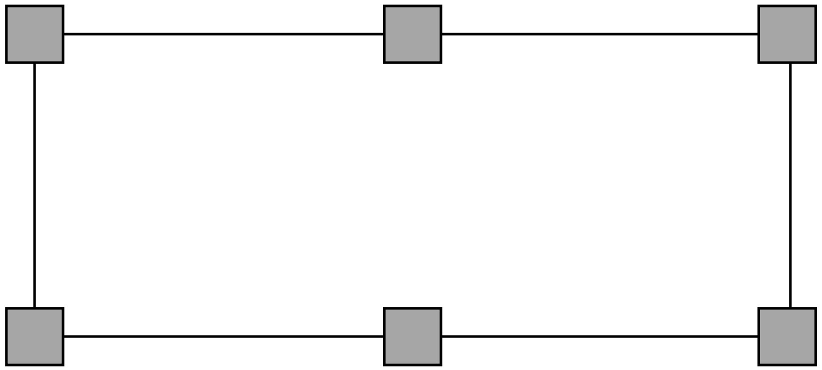
pre-sizing of foundations

$$\text{Area foundation} = \frac{\text{load}_{\text{building}}}{\text{capacity}_{\text{sol}}}$$

$$\text{dim foundation} = \frac{\text{Area foundation}}{\#\ \text{fondations}}$$

$$\text{Area foundation} = \frac{2400}{440} = 5.45\ \text{m}^2$$

$$\text{dim fondation} = \frac{5.45}{6} = 0.91\ \text{m}^2 = 1\text{x}1\ \text{m}$$



Structural Design & Environmental Impact

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EPFL

STRUCTURAL XPLORATION LAB