SAVING THE PLANET, A NEW CHALLENGE FOR STRUCTURAL ENGINEERS

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INFRARISK - Analysis and Mitigation of Risks in Infrastructures
8th Summer School Workshop

Faculty of Engineering, University of Porto (FEUP), Portugal, 04/11/2022

Structural Engineering – we have come a long way…

Ancient Egyptian Temple of Karnak, ∽ 1200 BC

Structural Engineering – we have come a long way…

Segovia Aqueduct, Segovia, ∽ 80 AD

Structural Engineering – we have come a long way…

The Pantheon, Rome, ∽ 120 AD

Structural Engineering – we have come a long way…

Hagia Sophia Grand Mosque, Istanbul, ∽ 530 AD

Structural Engineering – we have come a long way…

Notre-Dame Cathedral, Paris, 1163

Structural Engineering – we have come a long way…

Luís I Bridge, Porto, 1886

Structural Engineering – we have come a long way…

Empire State Building
New York, 1930

Burj Khalifa, Dubai, 2004

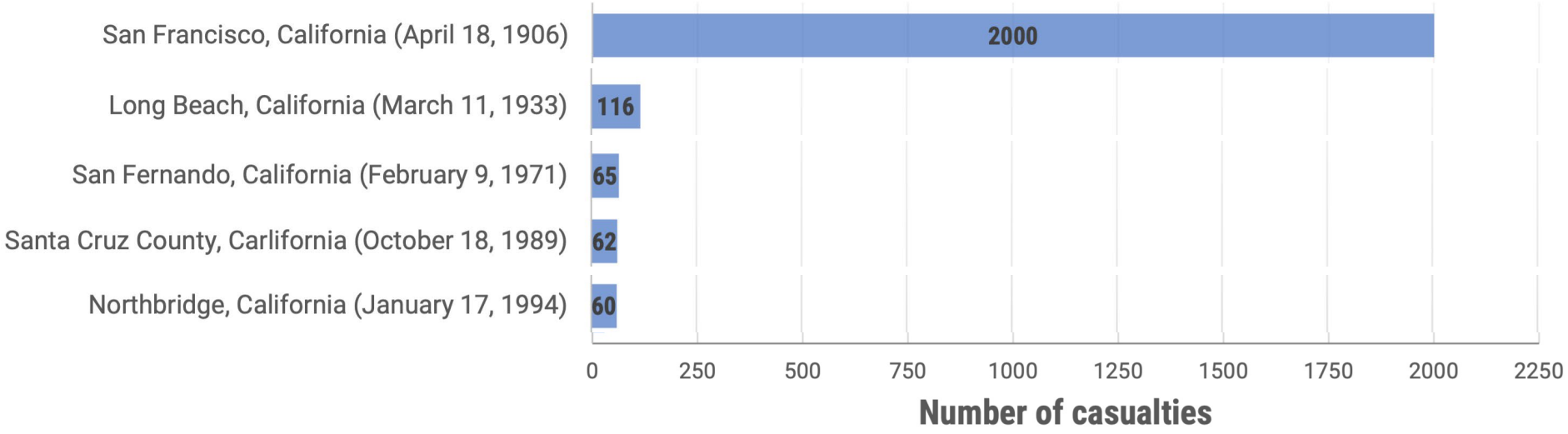
Structural Engineering – we have come a long way…

Marina Bay Sands, Singapore, 2009

Structural Engineering – we have come a long way…

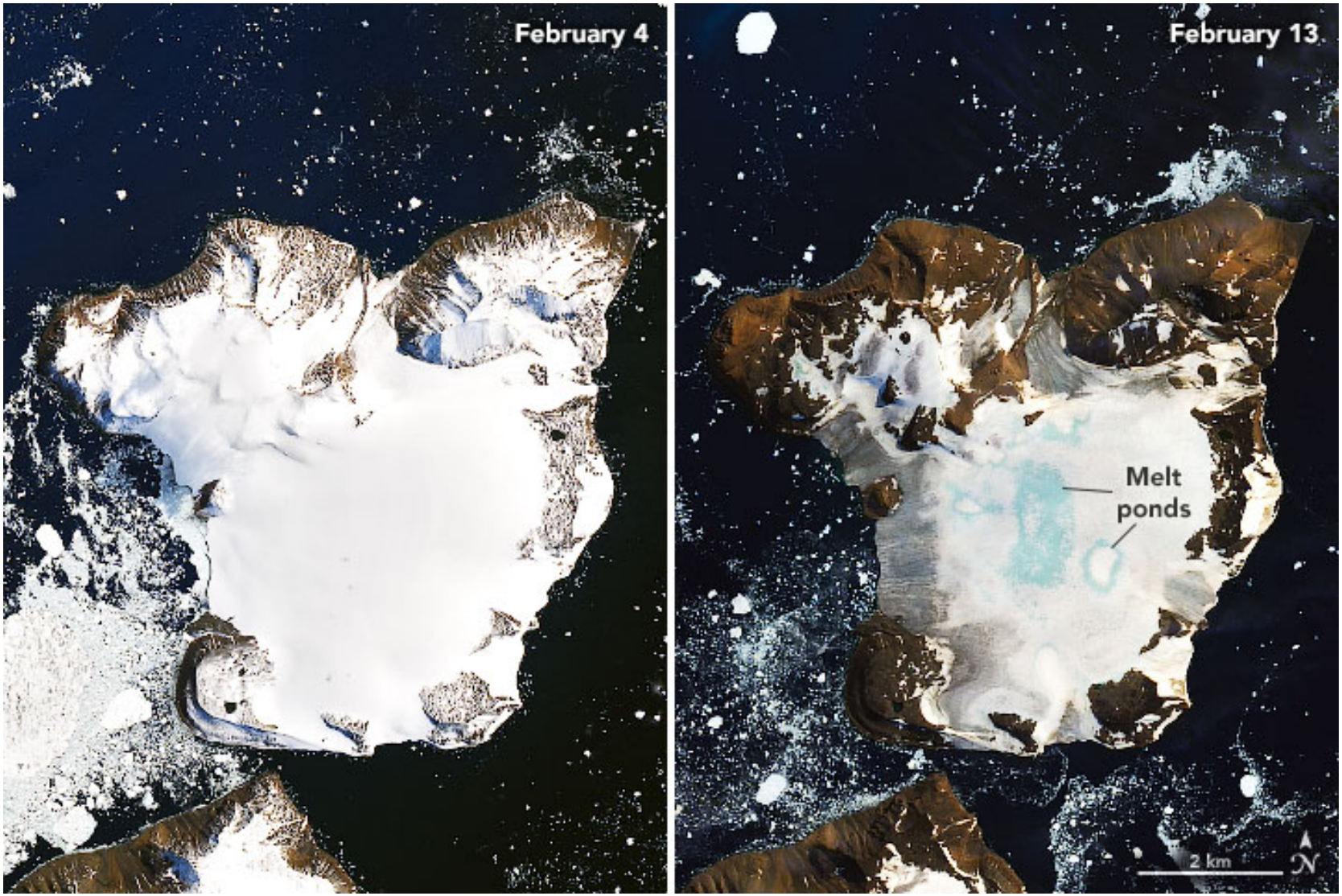
Sky Mile Tower, Tokyo, 2045

Structural Engineering advancements have saved lives (and continue to do so)…



But now also the Planet needs saving…

But now also the Planet needs saving…



Melting glaciers, Antarctica, 2020

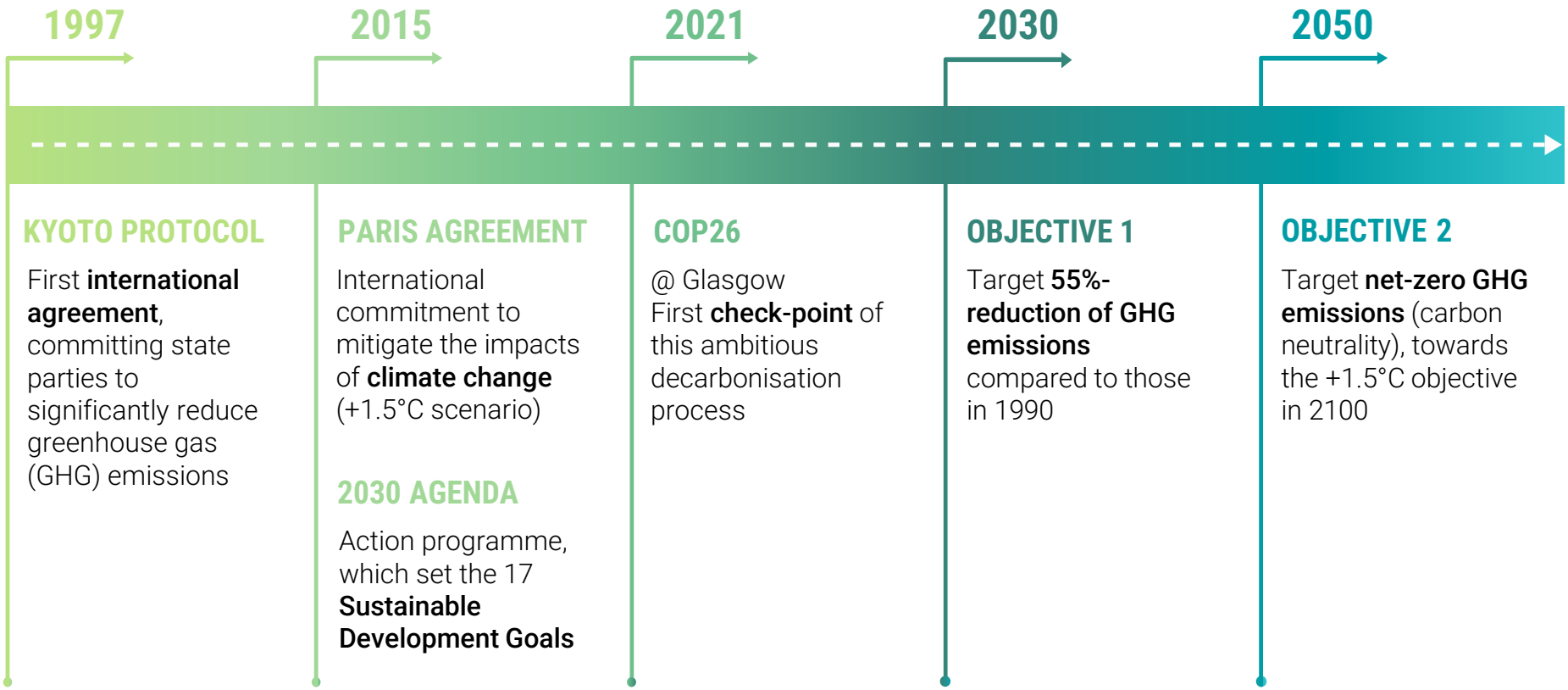
But now also the Planet needs saving…

Floods, Brisbane, 2022

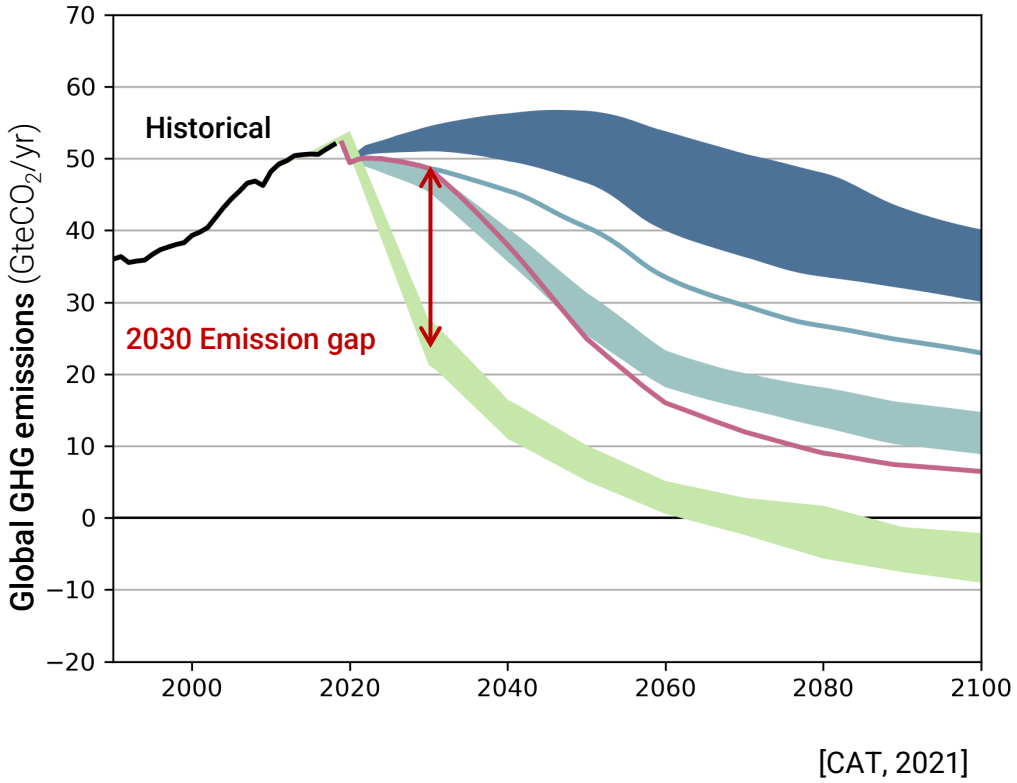
But now also the Planet needs saving…

Drought, Po river, Cremona, 2022

Sustainable development: targets and objectives



Sustainable development: are we on track?



[CAT, 2021]

Policies&Actions
+2.5/+2.9°C

2030 targets only
+2.4°C

Pledges&Targets
+1.9/+2.1°C

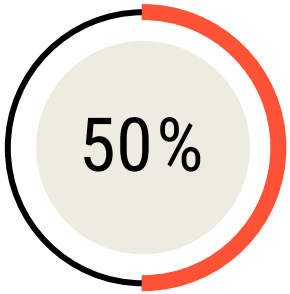
Optimistic scenario
+1.8°C

1.5°C scenario
+1.3/+1.5°C

What happens if we fail to reach our goals?

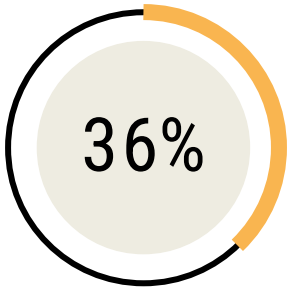
- Extreme weather events (e.g. tornados, floods)
- Rising sea levels and melting glaciers
- Desertification and land degradation
- Climate migration
- Loss of wildlife and biodiversity
- Climate-sensitive diseases and pandemics
- Mortality rate increase
- Food and water scarcity

The construction sector is responsible for…



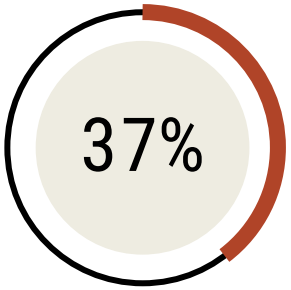
Raw materials

extraction for construction and retrofitting activities



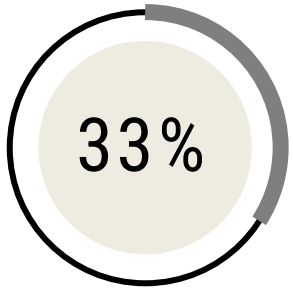
Energy consumption

for residential, non-residential and buildings construction industry



CO_2 emissions

for residential, non-residential and buildings construction industry



Waste production

due to construction and demolition activities

[GlobalABC, 2021]

Strategies towards buildings sustainability

1 **Energy demand**

Reduction of energy consumption

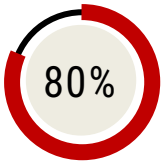
2 **Power supply**

Use of zero-energy technologies

3 **Embodied carbon**

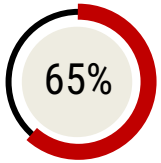
Limitation of CO_2 in construction materials

However, in e.g. the European building stock…



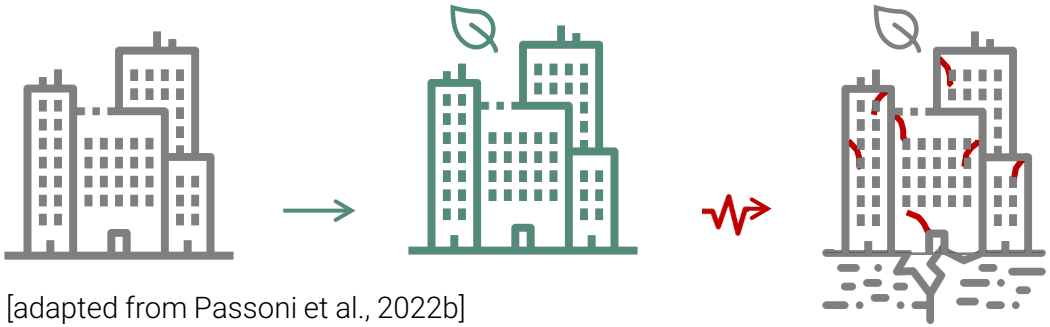
of buildings was built **before 1990**

of buildings is located in **seismic regions**



of buildings needs **integrated energy and seismic retrofitting**

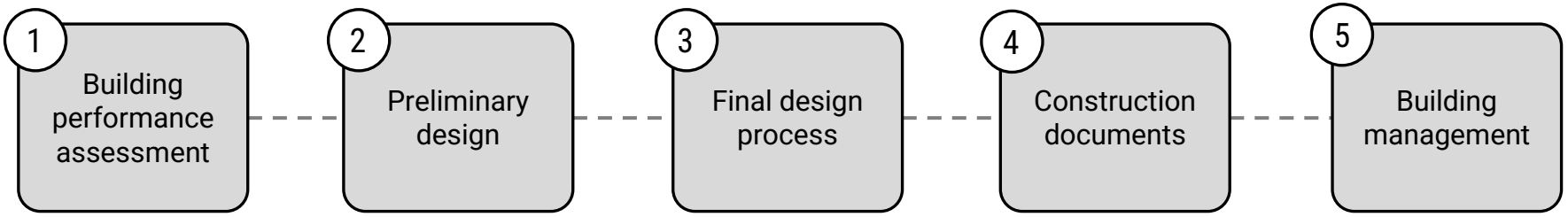
[Gkatzogias et al., 2021]



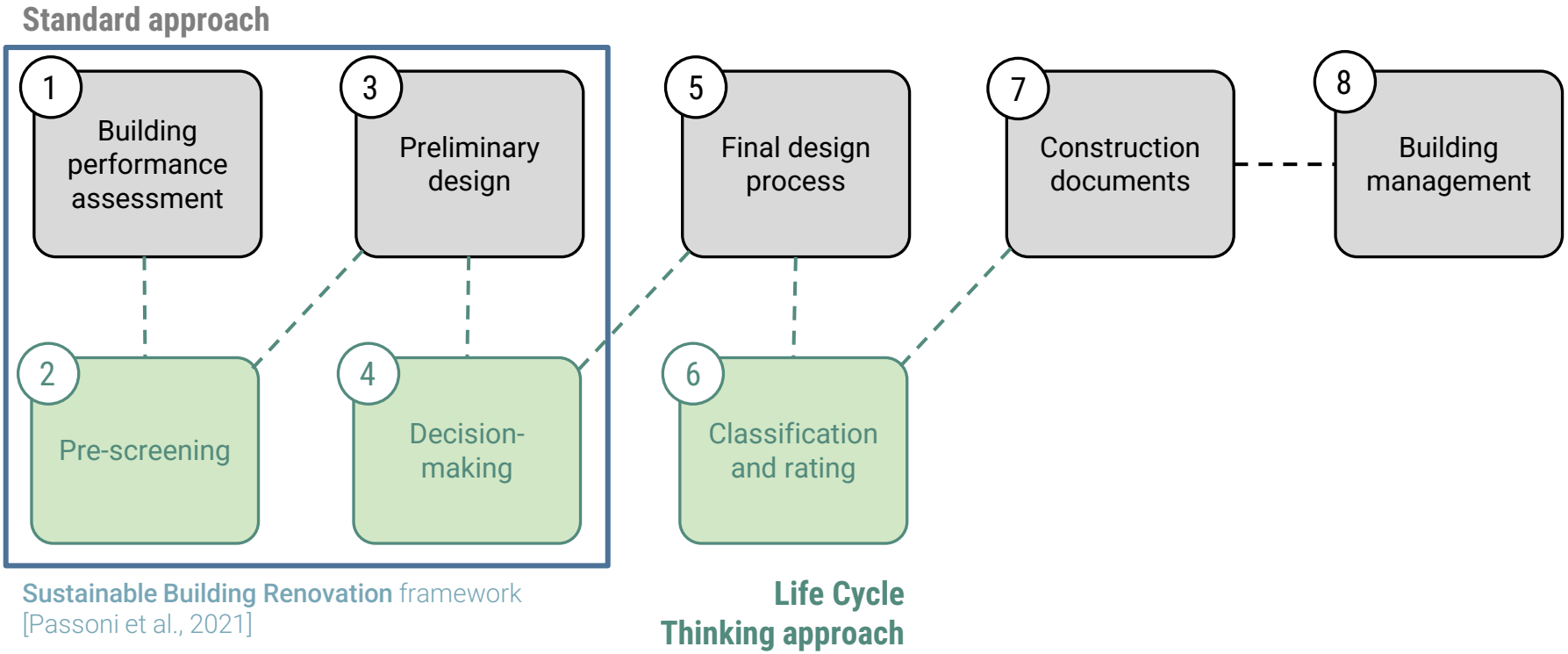
[adapted from Passoni et al., 2022b]

Life Cycle Structural Engineering: the future of design and retrofitting

Standard approach

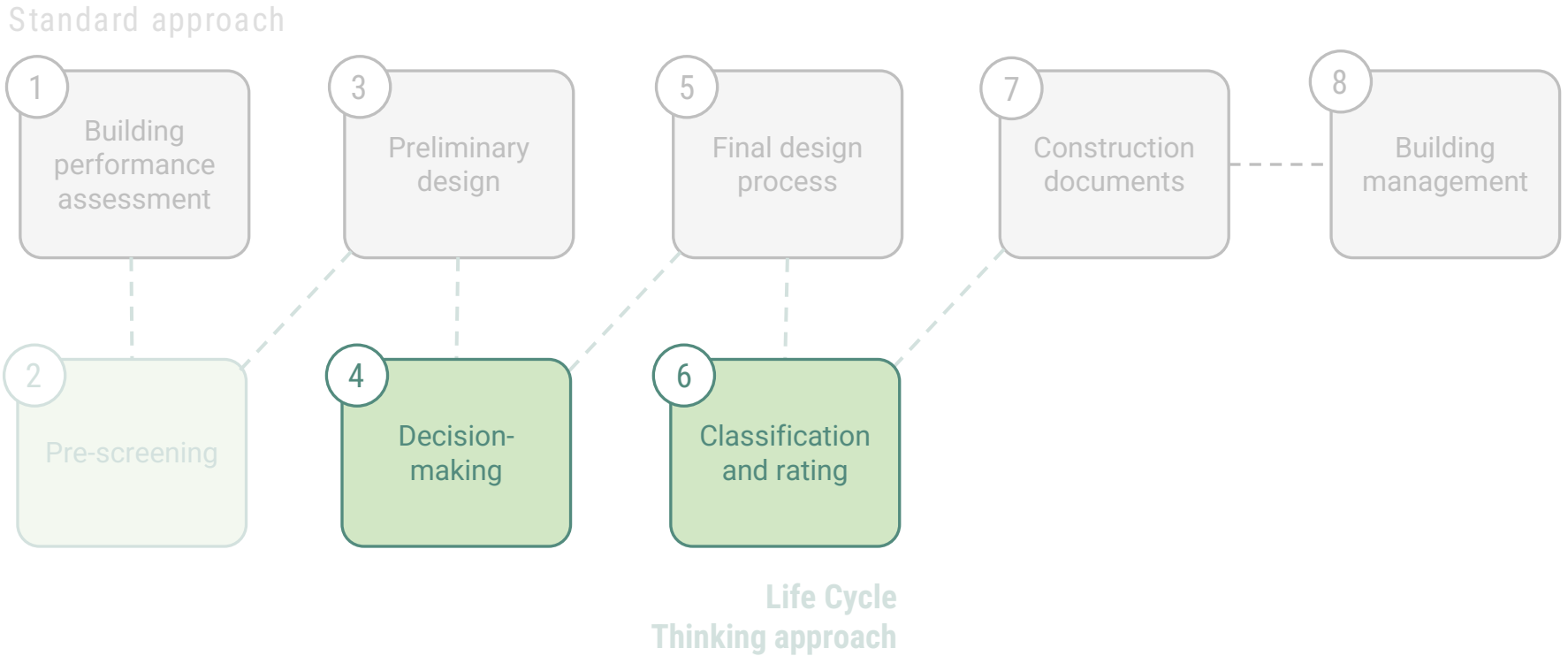


Life Cycle Structural Engineering: the future of design and retrofitting



[Passoni et al., 2022a]

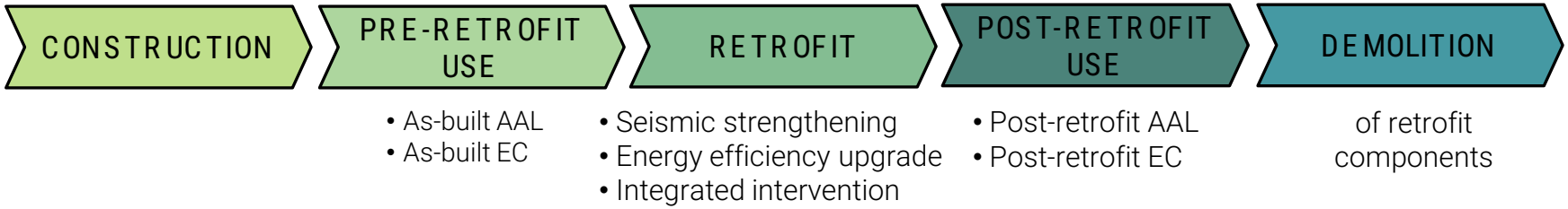
Life Cycle Structural Engineering: the future of design and retrofitting



[Caruso et al., 2020-2021-2022]

Decision-making approach for integrated assessment and retrofitting

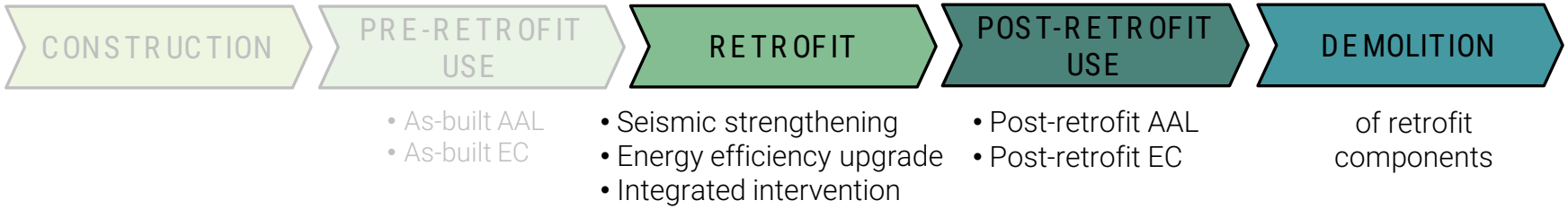
Building Life Cycle



[AAL: average annual loss; EC: annual energy consumption]

Decision-making approach for integrated assessment and retrofitting

Post-retrofit building Life Cycle



[AAL: average annual loss; EC: annual energy consumption]

Economic impacts

- cost of retrofitting
- expected seismic economic losses
- possible downtime due to seismic events
- cost of energy consumption
- payback period of the retrofit investment

Environmental impacts

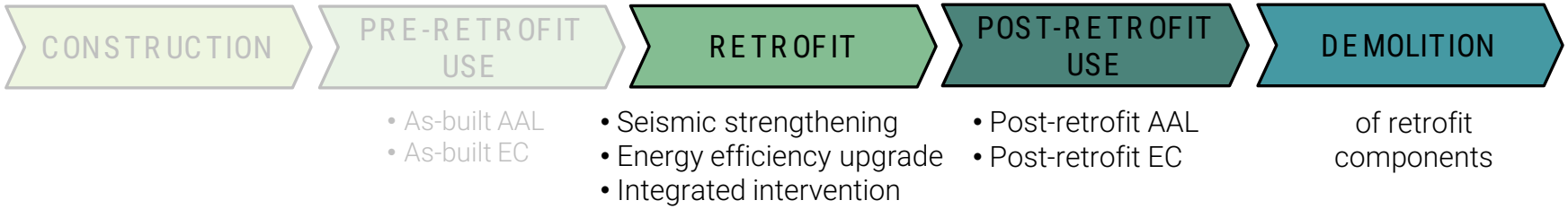
- carbon emissions of the retrofitting intervention
- expected carbon emissions due to earthquake-induced damage and repair activities
- carbon emissions due to energy consumption

Social impacts

- expected life losses due to seismic events

Decision-making approach for integrated assessment and retrofitting

Post-retrofit building Life Cycle



[AAL: average annual loss; EC: annual energy consumption]

Economic impacts

- cost of retrofitting
- expected seismic economic losses
- possible downtime due to seismic events
- cost of energy consumption
- payback period of the retrofit investment

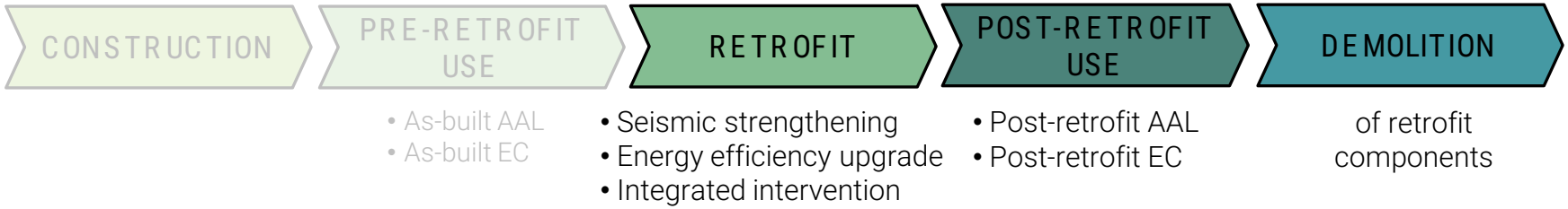
Parameter 1 (Life cycle costs)

$$\mathrm{LCPM}_{€} = \frac{\mathrm{RI} + (\mathrm{AAL}_{\text{post-retrofit}} + \mathrm{EC}_{\text{post-retrofit}}) \cdot \mathrm{SL}_2 + \mathrm{D(RI)}}{\mathrm{FA} \cdot \mathrm{SL}_2}$$

[LCPM: life cycle performance metric; RI: retrofitting intervention; SL_2: post-retrofit service life; D(RI): demolition of retrofit components; FA: floor area]

Decision-making approach for integrated assessment and retrofitting

Post-retrofit building Life Cycle



[AAL: average annual loss; EC: annual energy consumption]

Economic impacts

- cost of retrofitting
- expected seismic economic losses
- possible downtime due to seismic events
- cost of energy consumption
- payback period of the retrofit investment

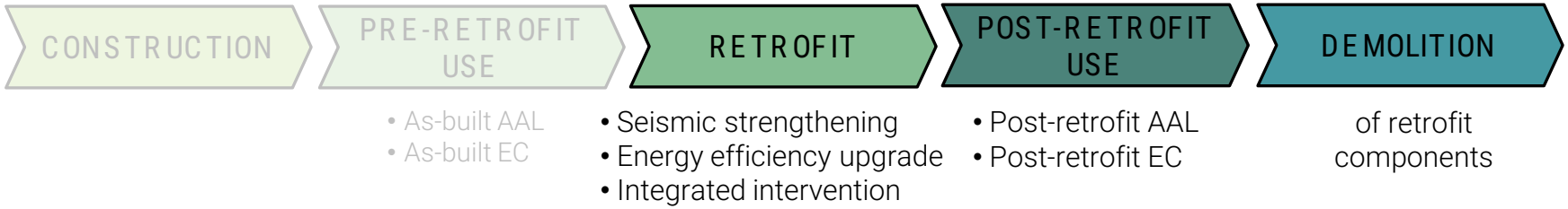
Parameter 2 (Payback period)

$$t \quad \text{such that} \quad \text{NPV} = \sum_{t=0}^{\text{SL}_2} \left[\frac{\Delta \text{AAL}}{(1+r_d)^t} + \frac{\Delta \text{EC}}{(1+r_d)^t} \right] - \text{RI} = 0$$

[t: years from the retrofitting intervention; NPV: net present value; r_d: discount rate]

Decision-making approach for integrated assessment and retrofitting

Post-retrofit building Life Cycle



[AAL: average annual loss; EC: annual energy consumption]

Environmental impacts

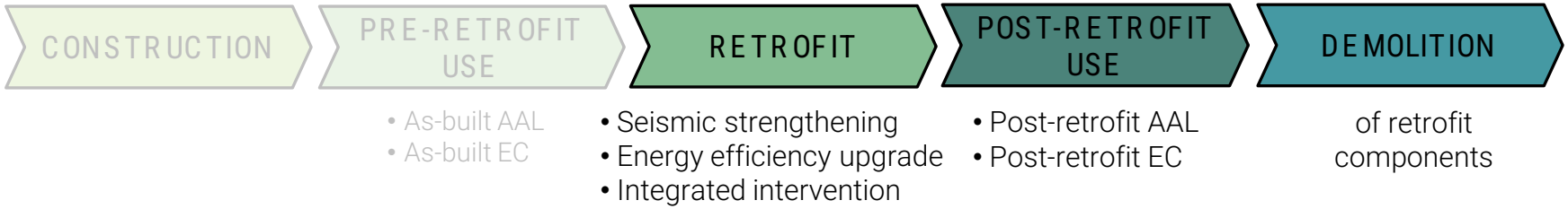
- carbon emissions of the retrofitting intervention
- expected carbon emissions due to earthquake-induced damage and repair activities
- carbon emissions due to energy consumption

Parameter 3 (Life cycle carbon emissions)

$$\mathrm{LCPM}_{\mathrm{kg\,eCO_2}} = \frac{\mathrm{RI} + (\mathrm{AAL}_{\text{post-retrofit}} + \mathrm{EC}_{\text{post-retrofit}}) \cdot \mathrm{SL}_2 + \mathrm{D(RI)}}{\mathrm{FA} \cdot \mathrm{SL}_2}$$

Decision-making approach for integrated assessment and retrofitting

Post-retrofit building Life Cycle



[AAL: average annual loss; EC: annual energy consumption]

Social impacts

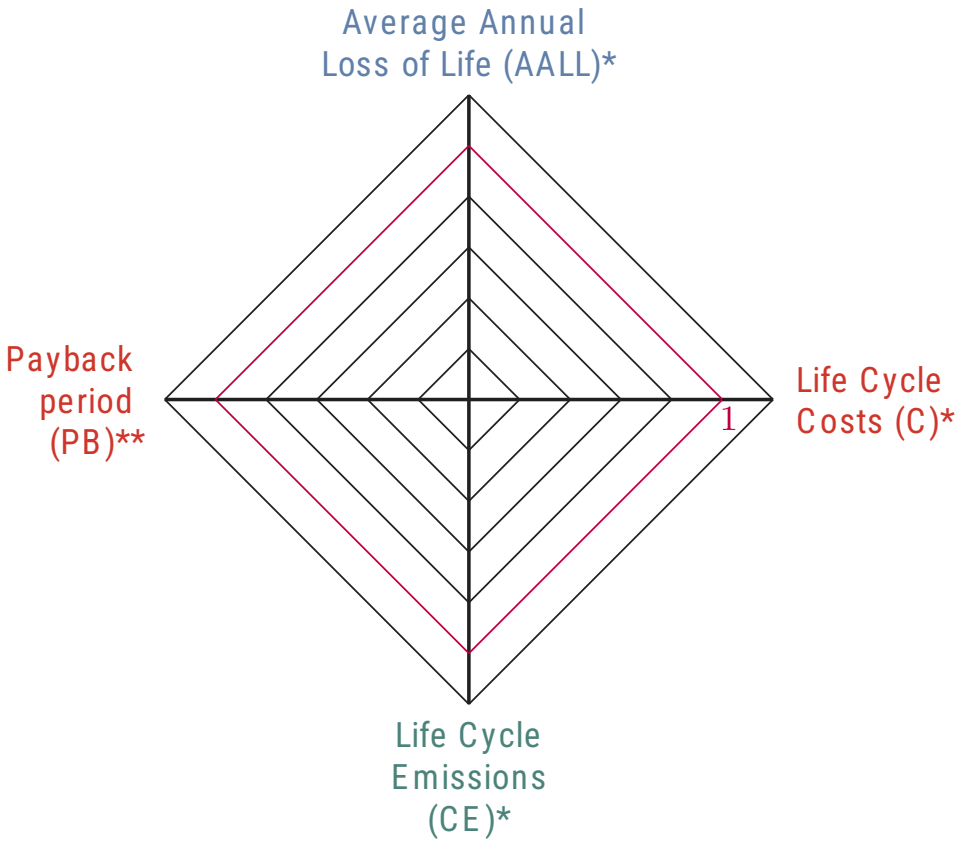
- expected life losses due to seismic events

Parameter 4 (Expected casualties due to seismic hazard)

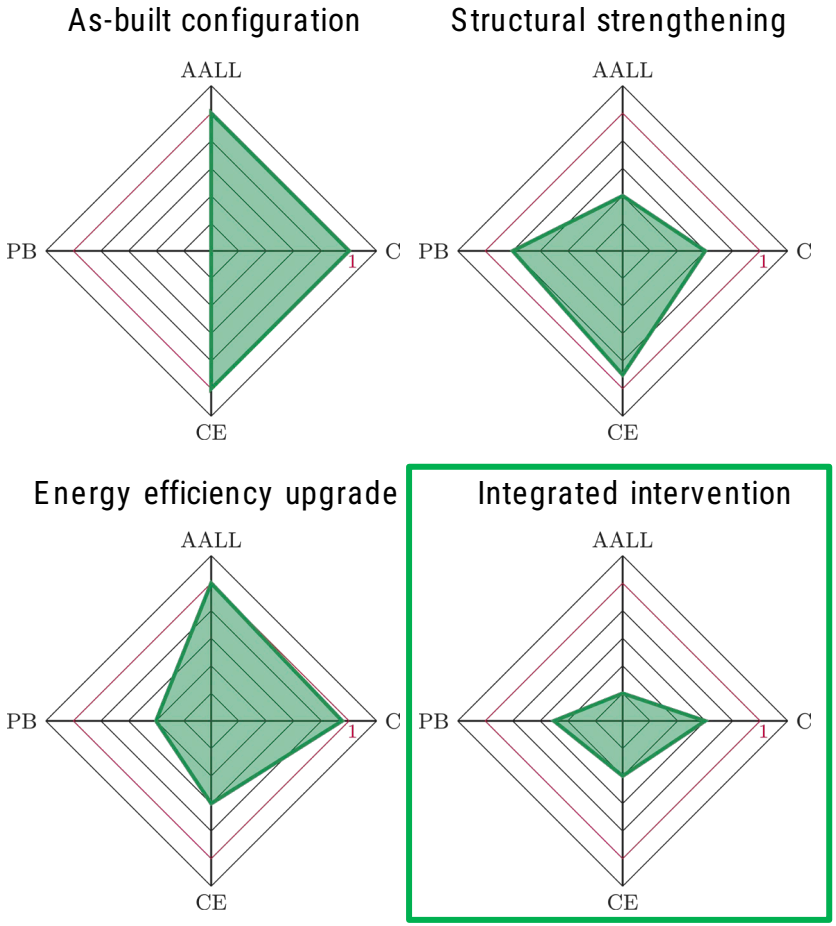
$$\lambda(\mathrm{DV}|\mathrm{O}) = \iiint P(\mathrm{DV}|\mathrm{DM},\mathrm{O})P(\mathrm{DM}|\mathrm{EDP},\mathrm{O})P(\mathrm{EDP}|\mathrm{IM},\mathrm{O})P(\mathrm{IM}|\mathrm{O})\,\mathrm{dIM}\,\mathrm{dEDP}\,\mathrm{dDM}$$

[DV: decision variable; O: building location and design; IM: intensity measure; EDP: engineering demand parameter; DM: damage measure]

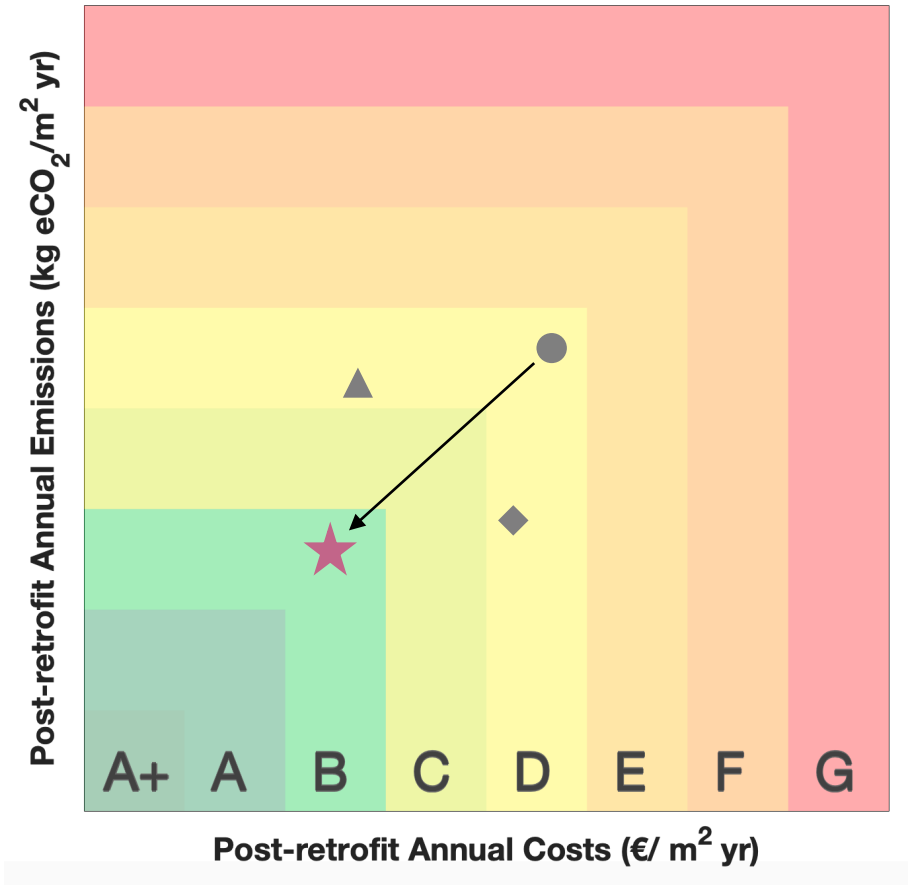
Decision-making approach for integrated assessment and retrofitting



*normalised by the corresponding values in the as-built configuration
**normalised with respect to the extended post-retrofit life of the building

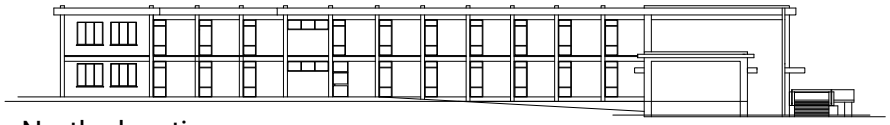


Integrated classification



Case-study applications

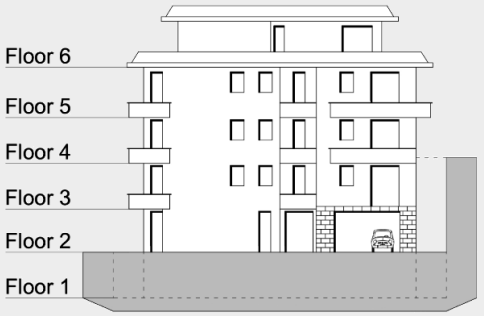
School building (Abruzzo, Italy)



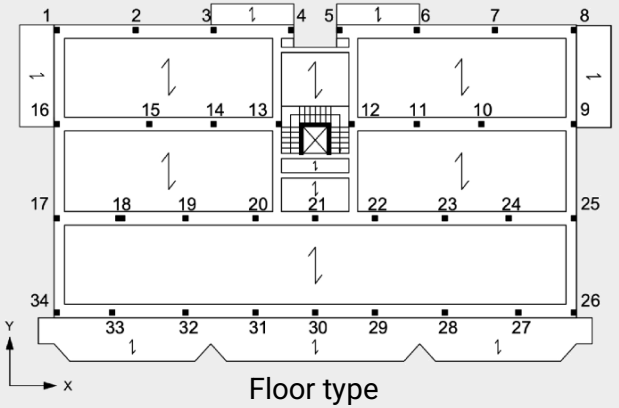
North elevation

South elevation

Residential building (Liguria, Italy)



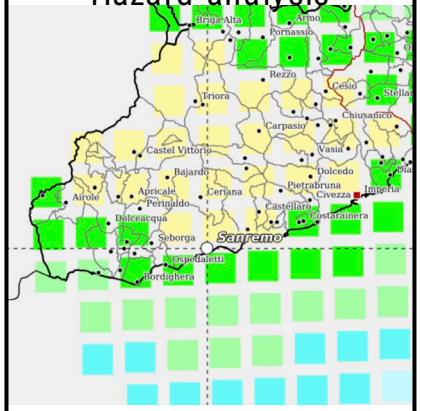
East elevation



Floor type

Earthquake loss assessment

Step 1: Hazard analysis

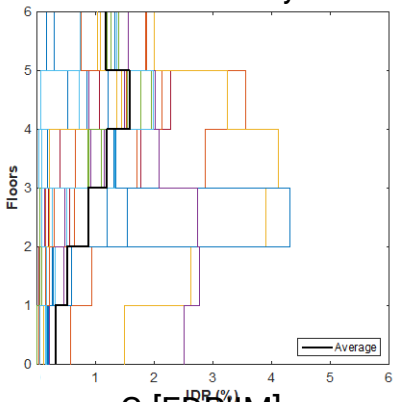


λ [IM|B,O]

IM: intensity measure

How frequently will an **event of intensity IM** occur, given the building B located in site O?

Step 2: Structural analysis

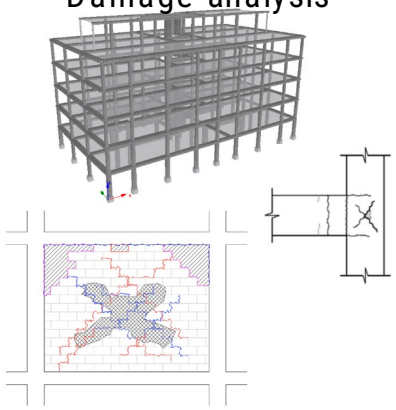


G [EDP|IM]

EDP: engineering demand parameter

What **engineering demand parameters** will the building's components be subjected to, given the occurrence of such an event?

Step 3: Damage analysis



G [DM|EDP]

DM: damage measure

What **damage** will the building's components experience, given the attainement of such engineering demands?

Step 4: Loss analysis

G [DV|DM]

DV: decision variable

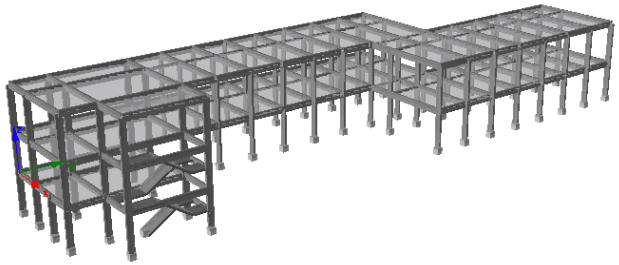
What **losses** will the building undergo, given the attainment of such damage states in its members?

[ATC (2018a-d), Cardone and Perrone (2015), Cardone (2016), Seismosoft (2022)]

Earthquake loss assessment

School building (Abruzzo, Italy)

- Pushover-based loss analysis;
- Consideration of direct costs only.



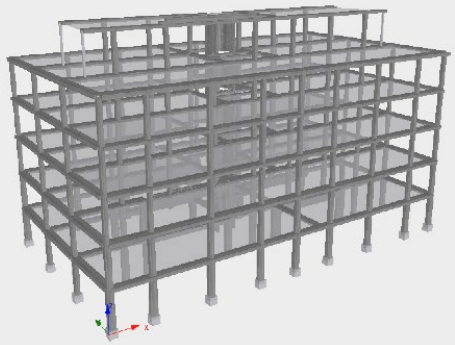
4,800 €/year
(0.38% of the replacement cost)

1,800 kg eCO_2/ year
(0.28% of the replacement impact)

0.03 expected casualties/year

Residential building (Liguria, Italy)

- NTHA-based loss analysis;
- Consideration of costs of downtime.



13,000 €/ year
(0.36% of the replacement cost)

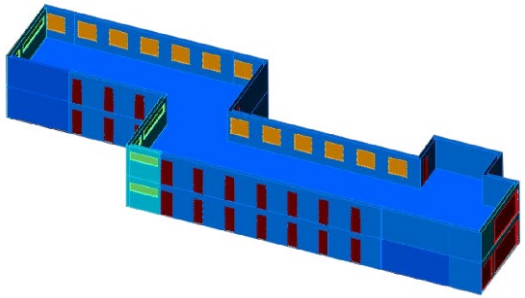
4,000 kg eCO_2/year
(0.27% of the replacement impact)

0.11 expected casualties/year

Energy performance assessment

School building (Abruzzo, Italy)

- Semi-stationary analysis;
- Contribution of heating only.

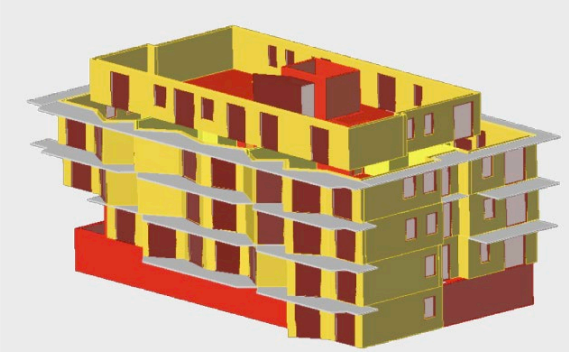


27,000 €/year
(2.16% of the replacement cost)

53,000 kg eCO_2/year
(8.15% of the replacement impact)

Residential building (Liguria, Italy)

- Dynamic analysis;
- Heating, cooling, hot water, elevator.

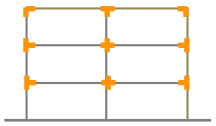


11,000 €/year
(0.30% of the replacement cost)

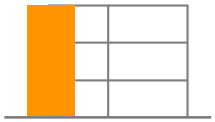
26,000 kg eCO_2/year
(1.66% of the replacement impact)

Retrofitting strategies: seismic strengthening

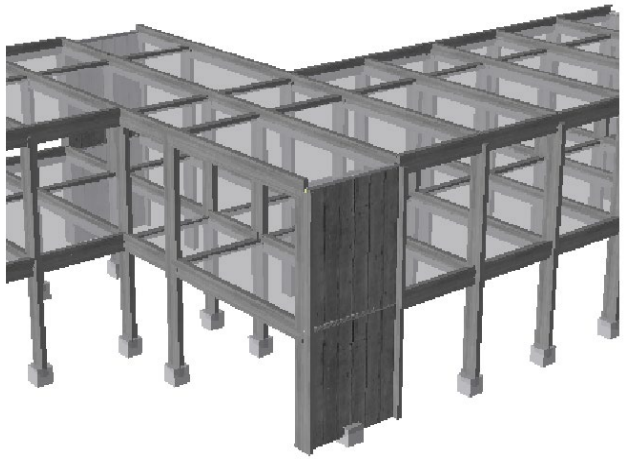
School building (Abruzzo, Italy)



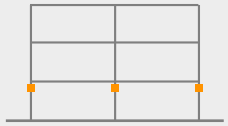
External joints strengthening (**'Joint_Strength' or JS**)



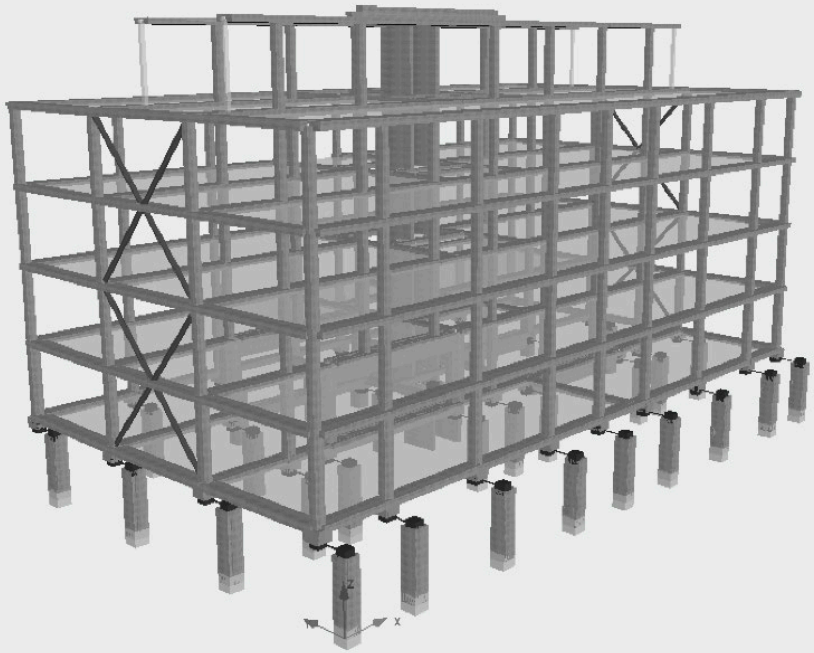
New RC shear walls (**'RC_Walls' or RCW**)



Residential building (Liguria, Italy)

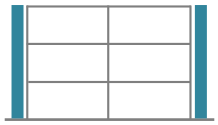


Seismic isolation and cross steel braces (**'Seism_Iso + St_Braces' or ISO + SB**)

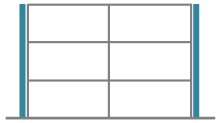


Retrofitting strategies: energy efficiency upgrade

School building (Abruzzo, Italy)

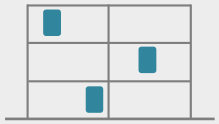


Vertical insulation coating in EPS panels
(**'ThermInsul' or TI**)



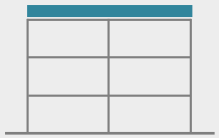
Ultra-thin ceramic insulation layer
(**'ceramic_ThermInsul' or cTI**)

Residential building (Liguria, Italy)

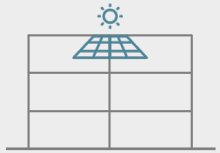


Energy-efficient windows
(**'Windows' or W**)

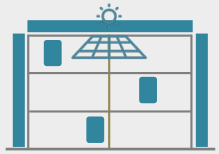
Thermal insulation of wall air gap with cellulose fibers
(**'Vert_Thermal_Insul' or VTI**)



Roof insulation coating in XPS panels
(**'Roof_Thermal_Insul' or RTI**)



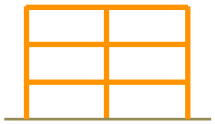
Photovoltaic system with multi-crystalline technology
(**'Photovoltaic' or PV**)



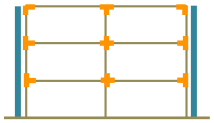
All energy efficiency interventions
(**'Wind + Vert_TI + Roof_TI + Photovoltaic' or W + VTI + RTI + PV**)

Retrofitting strategies: integrated interventions

School building (Abruzzo, Italy)



External joints strengthening + beams and columns coating (**'Joint_Strength + BC_Coat' or JS + bcC**)

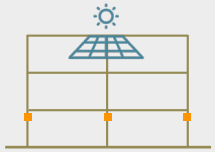


External joints strengthening + thin vertical insulation layer (**'Joint_Strength + thin_ ThermInsul' or JS + tTI**)

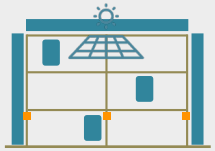
New RC shear walls + vertical insulation coating in EPS panels (**'RC_walls + ThermInsul' or RCW + TI**)

New RC shear walls + ultra-thin ceramic insulation layer (**'RC_walls + ceramic_ThermInsul' or RCW + cTI**)

Residential building (Liguria, Italy)



Seismic isolation and cross steel braces + photovoltaic system (**'Seism_Iso + St_Braces' + Photovoltaic' or ISO + SB + PV**)

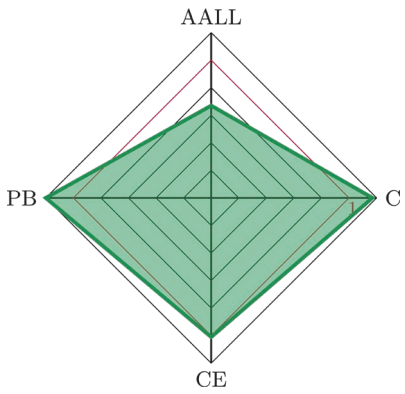


Seismic isolation and cross steel braces + all energy efficiency interventions (**'ISO + SB + W + Vert_TI + Roof_TI + Photovoltaic' or ISO + SB + W + VTI + RTI + PV**)

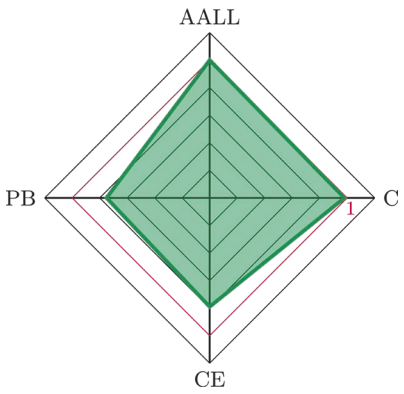
Identification of the optimal retrofitting strategies

School building (Abruzzo, Italy)

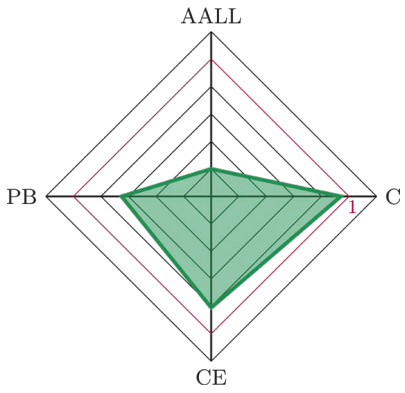
JS



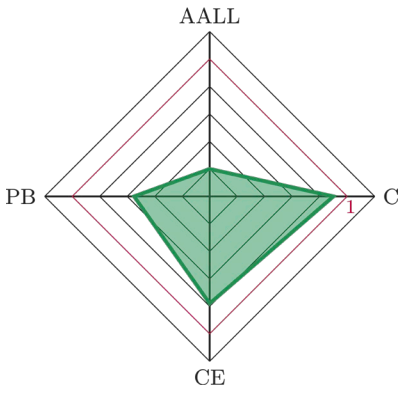
TI



RCW + cTI

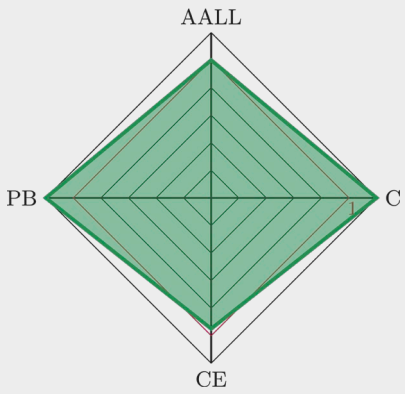


RCW + TI

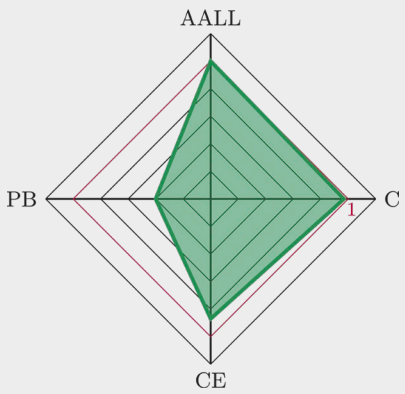


Residential building (Liguria, Italy)

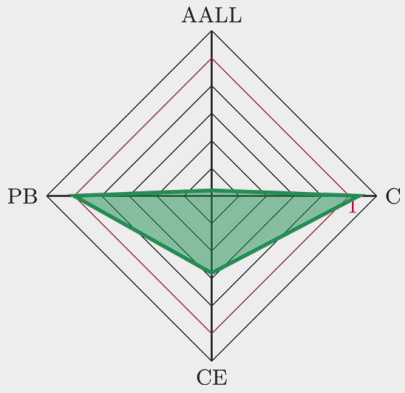
W



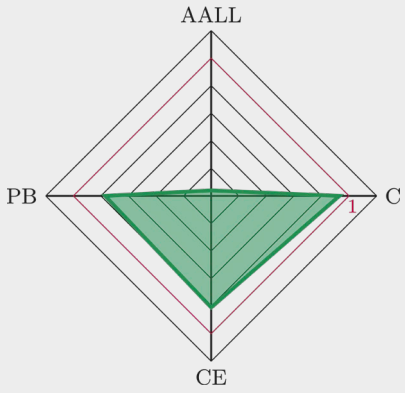
VTI



ISO+ SB + W + VTI + RTI + PV

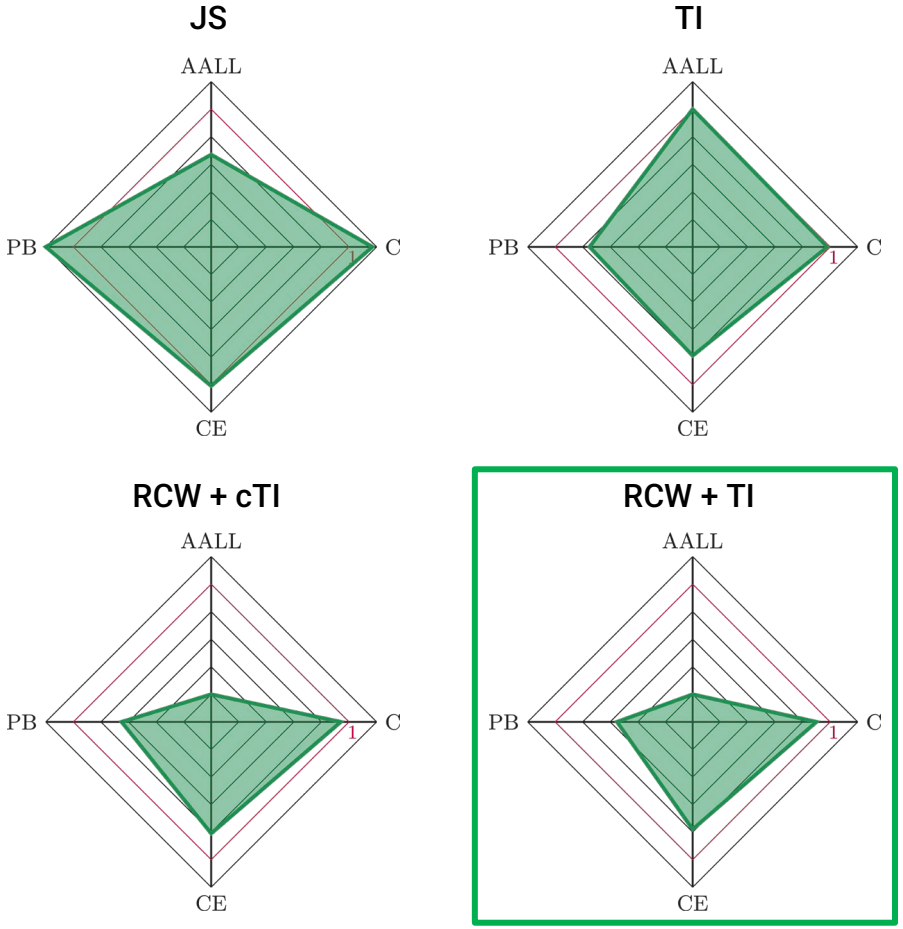


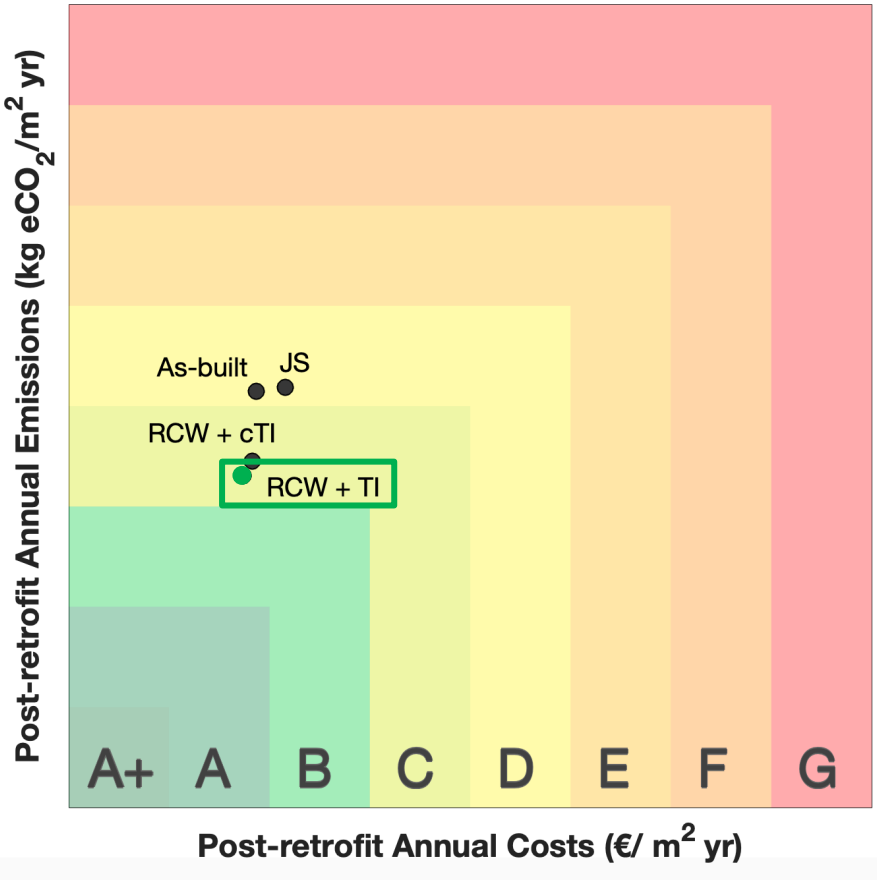
ISO + SB + PV



Integrated classification

School building (Abruzzo, Italy)





Optimal retrofitting strategies at different sites

School building (Abruzzo, Italy)

Mild_AvgEq

'RC_walls + ThermInsul'

Warm_HighEq

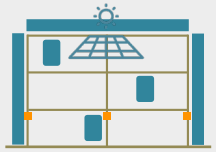
'RC_walls + ThermInsul'

Cold_LowEq

'RC_walls + ThermInsul'

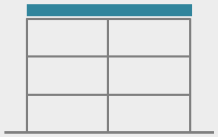
Residential building (Liguria, Italy)

Warm_AvgEq



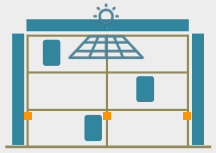
'ISO + SB + W + Vert_TI + Roof_TI + Photovoltaic'

Mild_LowEq



'Roof_Thermal_Insul'

Cold_HighEq



'ISO + SB + W + Vert_TI + Roof_TI + Photovoltaic'

Closure

Achieving buildings sustainability represents a main need of our time, thus we, as building/structural engineers, should all be deeply committed to such an ambitious purpose and challenge!

Life Cycle Structural Engineering is expected to become the standard approach for design and retrofitting in actual engineering practice, to foster buildings sustainability by improving their seismic and energy performances at the same time

Viable and practical approaches are now available for life cycle-based classification of buildings and for the identification of optimal retrofitting strategies based on economic, environmental and social decision-making parameters

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"This is Europe's man on the moon moment. Our goal is to reconcile the economy – the way we produce, the way we consume – with our planet and to make it work for our people."

(Ursula von der Leyen)

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