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A Method to Combine Safety, Energy Efficiency and Environmental Requirements in the Design of Buildings

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JRC.E.4 Safety and Security of Buildings

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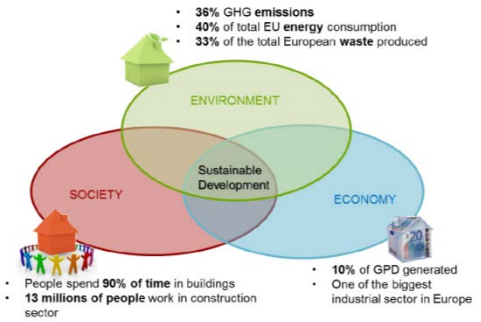
European Commission

Introduction

Sustainable development is one of the most relevant topics of the last decades

The European Commission interest in sustainable development is also evident considering the massive investments that have been, and still are, carried out to guarantee a sustainable approach to the growth.

Introduction



The construction industry is the sector contributing more to the environmental burden. Building sector is responsible of:

33% of GHG emissions including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)*

40% of the total EU energy consumption*

*Source: European Commission. Energy-efficient buildings - Multi-annual roadmap for the contractual PPP under Horizon 2020

Introduction

GLOBAL AGREEMENTS:

Kyoto Protocol (1997)
Paris Agreement (2015)

→

Directive of the Energy Performance of the Buildings (EPBD) (Directive 2010/31/UE)

global commitment in the reduction of climate change, focusing the attention on transports, agriculture and building sector.

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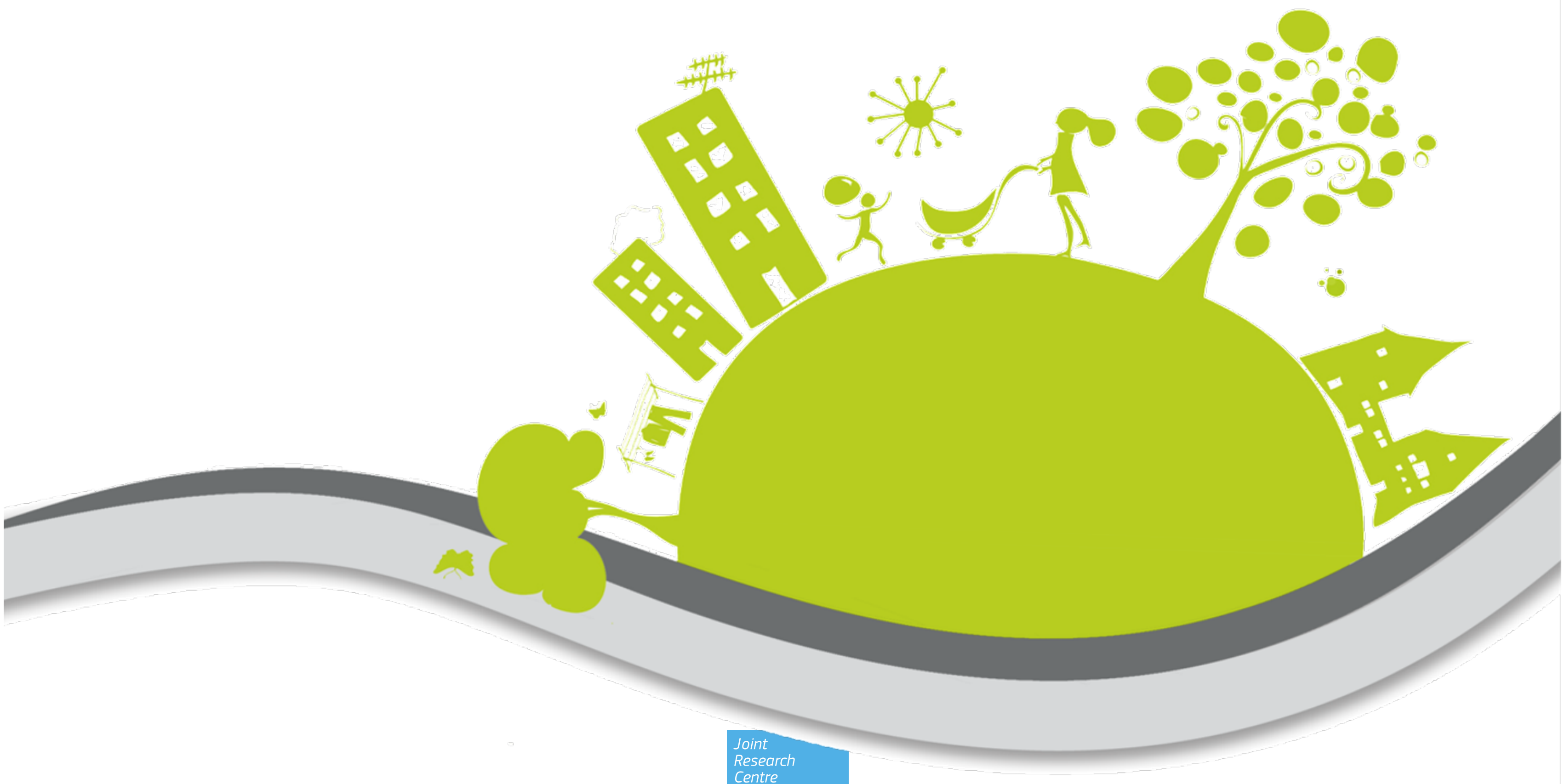
Introduction

Life-Cycle Analysis (LCA, from cradle to grave...)



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Life-Cycle Analysis (LCA, from cradle to grave…)

Many LCA assessment procedures….

- **Different criteria**
- **Lack interoperability**
- **Long and difficult**

- **Only a posteriori….**

Introduction

The growing interests in achieving the environmental goals of the global agreements might be prevailing on other aspects of sustainability of buildings, such as SAFETY

Roof collapse of a Municipal library in Sardinia, 2015

Emilia Region earthquake, 2012

A case history

During the first shock of Emilia earthquake (May 20th, 2012) some agricultural buildings collapsed.

The total estimated damage was assessed as 7M€, 2M€ the brand new PV plant only.

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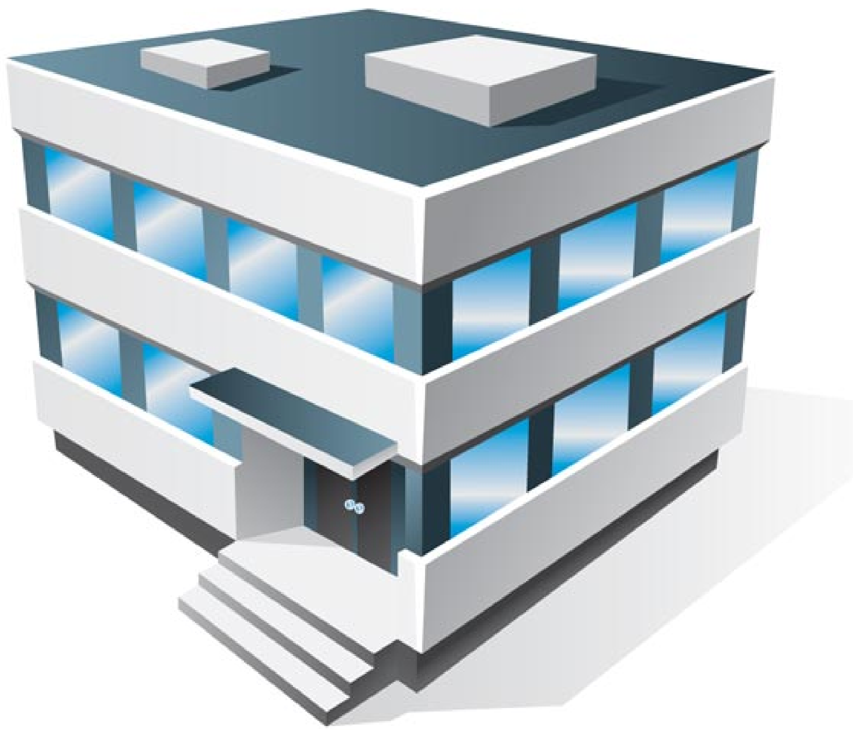

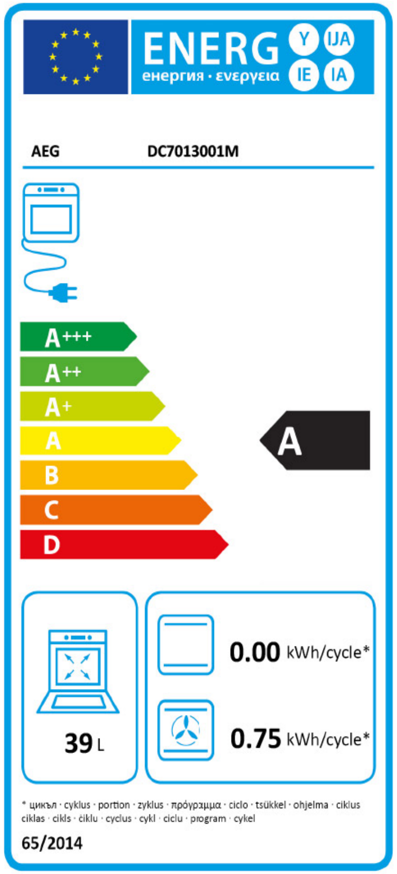

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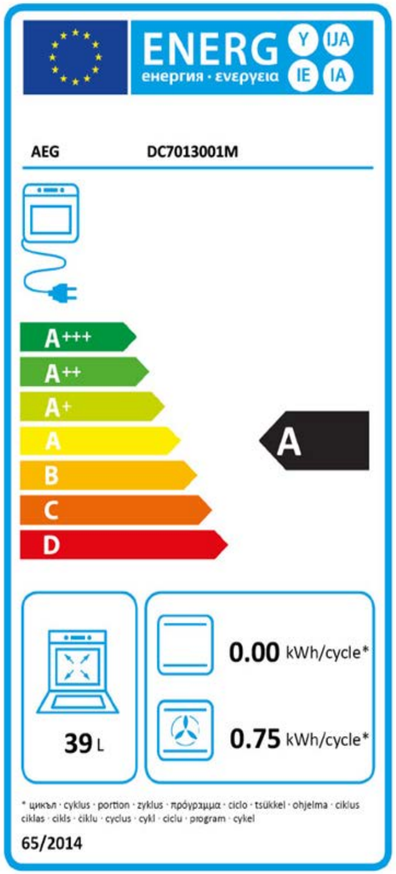

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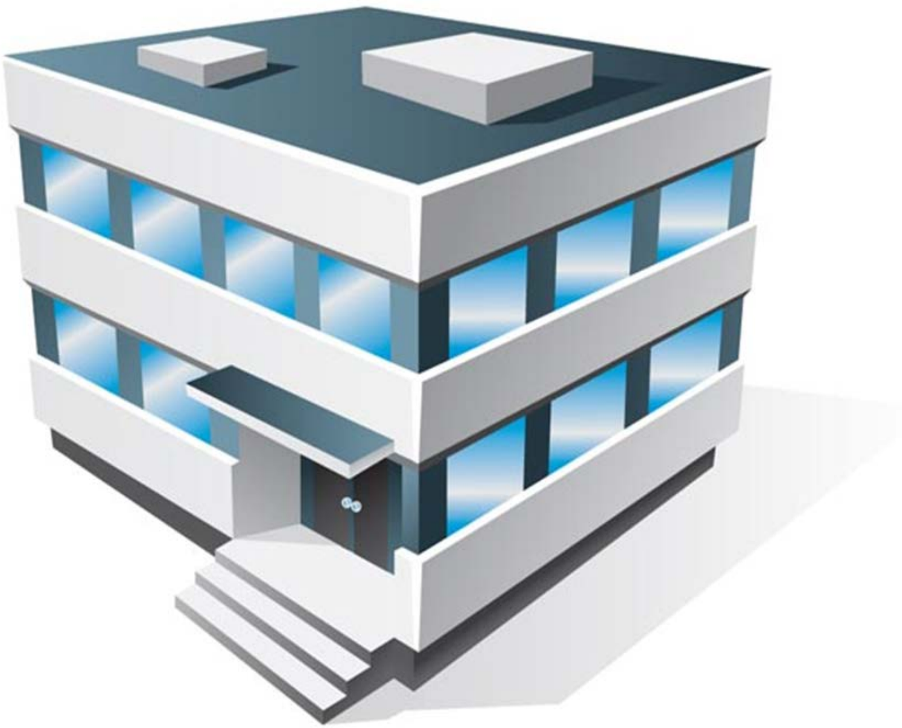

Look at the whole process

SSD Methodology

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Sustainable Structural Design (SSD) is a methodology aiming at supporting the general design process of buildings.

The methodology combines the structural and the environmental aspects of the buildings and summarises them in a single final parameter, provided in economic terms.

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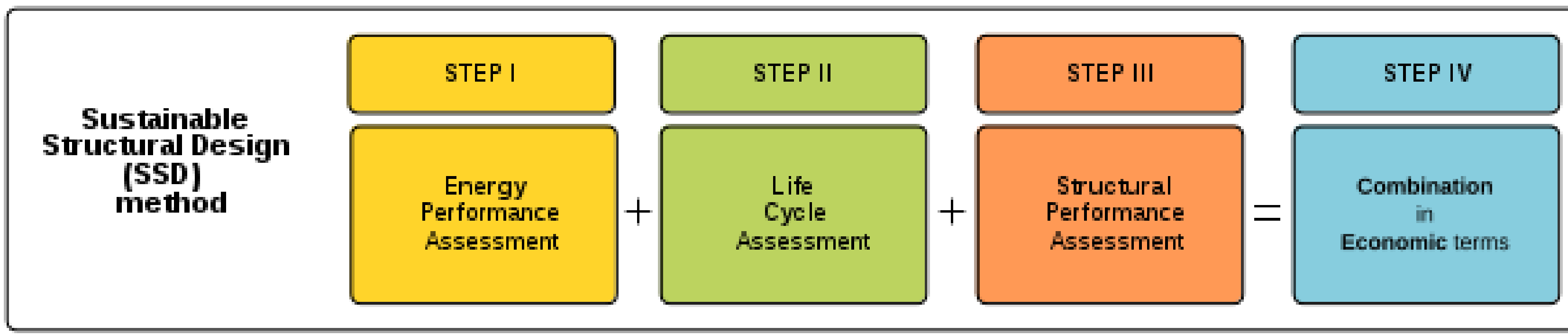
SSD Methodology

The framework of the SSD methodology is based on three main pillars, corresponding to the three evaluation steps:

- *Energy* Performance Assessment;
- *Life Cycle* Assessment;
- *Structural Performance* Assessment.



The last step aims at converting the results of the previous analyses into the same Unit of Measure, in economic terms.

The GLOBAL ASSESSMENT PARAMETER R_{SSD} *is provided*

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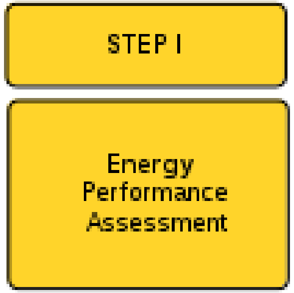
SSD Methodology



The energy performance assessment step is formally part of the Life-Cycle assessment step, but it is performed separately from the second step of the methodology in order to easily address the operational costs of the buildings

$$E_{LC} = E_E + E_O + E_D$$

In this phase, only E_O is evaluated because it is interesting to separate this value from the others for two reasons:

1. *European policies are moving towards the reduction of the energy consumptions, reaching the goal of the widespread diffusion of nearly zero energy buildings. Therefore, a control on operational energy should be guaranteed.*

2. *The energy prices can include energy taxes related to the carbon content. Having this value separately means to avoid the double inclusion of CO_2 contribution*

SSD Methodology

STEP II

Life Cycle Assessment

Life-Cycle Assessment (LCA) is a methodology aiming at the evaluation of the environmental impacts of products and processes generated during their entire life cycle

1. Goal and Scope — G&S
2. Life Cycle Inventory — LCI
3. Life Cycle Impact — LCIA
4. Life Cycle INterpretation — LCIN

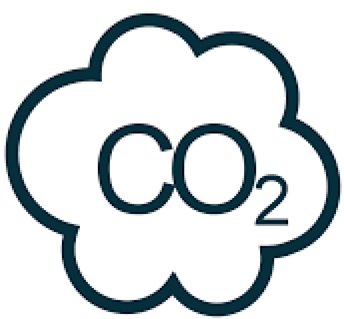
4 major stages of the LCA (EN 15978)

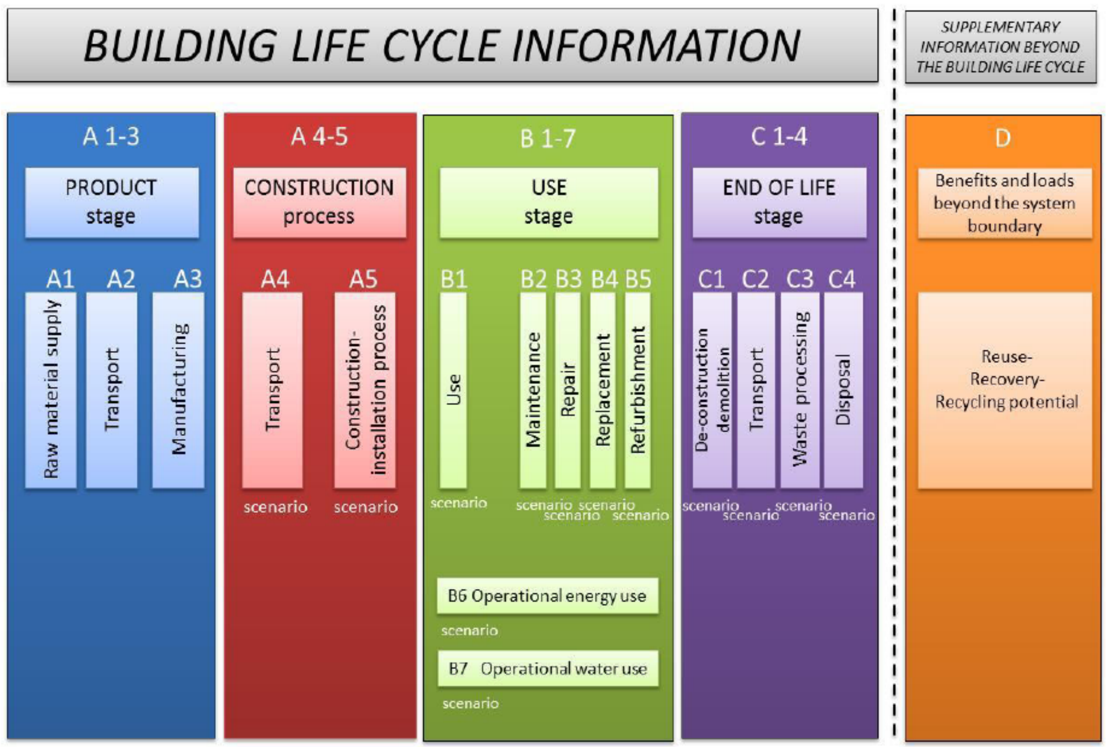
SSD Methodology

STEP II

Life Cycle Assessment

The Life-Cycle Assessment (LCA) is a methodology aiming at the evaluation of the environmental impacts of products and processes generated during their entire life cycle





Definition of the life-cycle stages and system boundary for buildings according to EN 15978

SSD Methodology

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STEP III

Structural Performance Assessment

Performance-based approach was born after the earthquakes in Northridge (1994) and Kobe (1995), which have led to a complete re-examination of the building sector knowledge: PEER approach.

Involves the implementation of probabilistic scenarios the structure could face during its lifespan.

Design is treated in a probabilistic manner, with objectives that represent the cost of construction, but also the cost of expected repair measures and downtime losses.

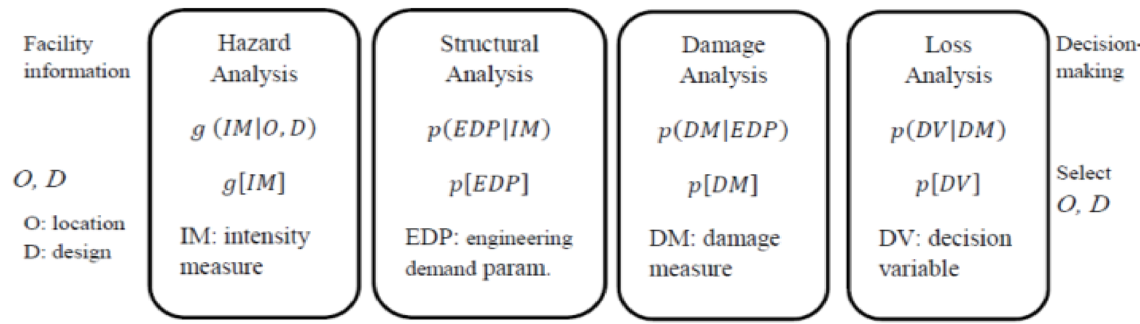
The decision is made in terms of costs.

SSD Methodology

STEP III

Structural Performance Assessment

The PEER PBEE (Performance Based Earthquake Engineering) methodology is divided into four steps



IM can be: PGA, Sa, Sv

EDP can be: interstorey drifts, floor accelerations

DM can be: slight, heavy, severe, collapse

DV can be: economic loss, injuries, fatalities

PBEE suggests to evaluate the losses as follows:

$$G\,(DV) = \iiint_0^{\infty} G(DV|DM) \left|\frac{dG(DM|EDP)}{dDM}\right| \left|\frac{dG(EDP|IM)}{dEDP}\right| dIM\; dEDP\; dDM$$

SSD Methodology

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STEP III

Structural Performance Assessment

Negro and Mola (2015) suggested a simplified methodology to evaluate the earthquake losses of buildings (sPBA).

In phase 1, limit states are defined (low damage, heavy damage, severe damage and loss of the building/collapse) and the expected costs related to each limit state are evaluated. The structural damage is evaluated in terms of the inter-storey drift (IDR)

In phase 2, the evaluation of the peak ground accelerations (PGAs) causing the IDR values defined at the previous step is performed, through skeleton curves obtained from IDA or from Pushover analysis

SSD Methodology

STEP III

Structural Performance Assessment

In phase 3, the PGAs provided by the previous step are converted in probability of exceedance, by using the return periods provided for each PGA by national codes and the following expression:

$$R_N = 1 - \left(1 - \frac{1}{T_R}\right)^N$$

In phase 4, the economic losses are evaluated summing the product of the probability of exceedance and repair/replacement costs, at each limit state:

$$L = \sum_{i=1} C_i \cdot (R_i - R_{i+1})$$

SSD Methodology

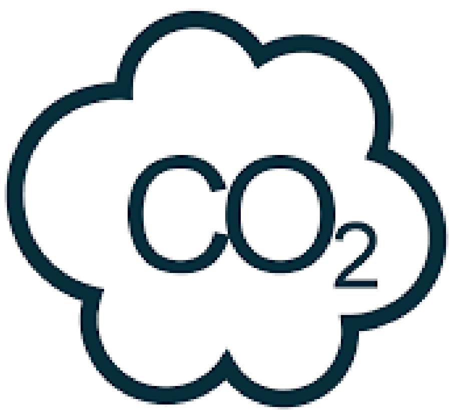
STEP III

Structural Performance Assessment

The total cost (i.e., Investment and Expected losses) for structural performance assessment is evaluated with the following expression

$$C_{TOT} = I + L$$

where I is the initial construction costs of the building.


CO_2

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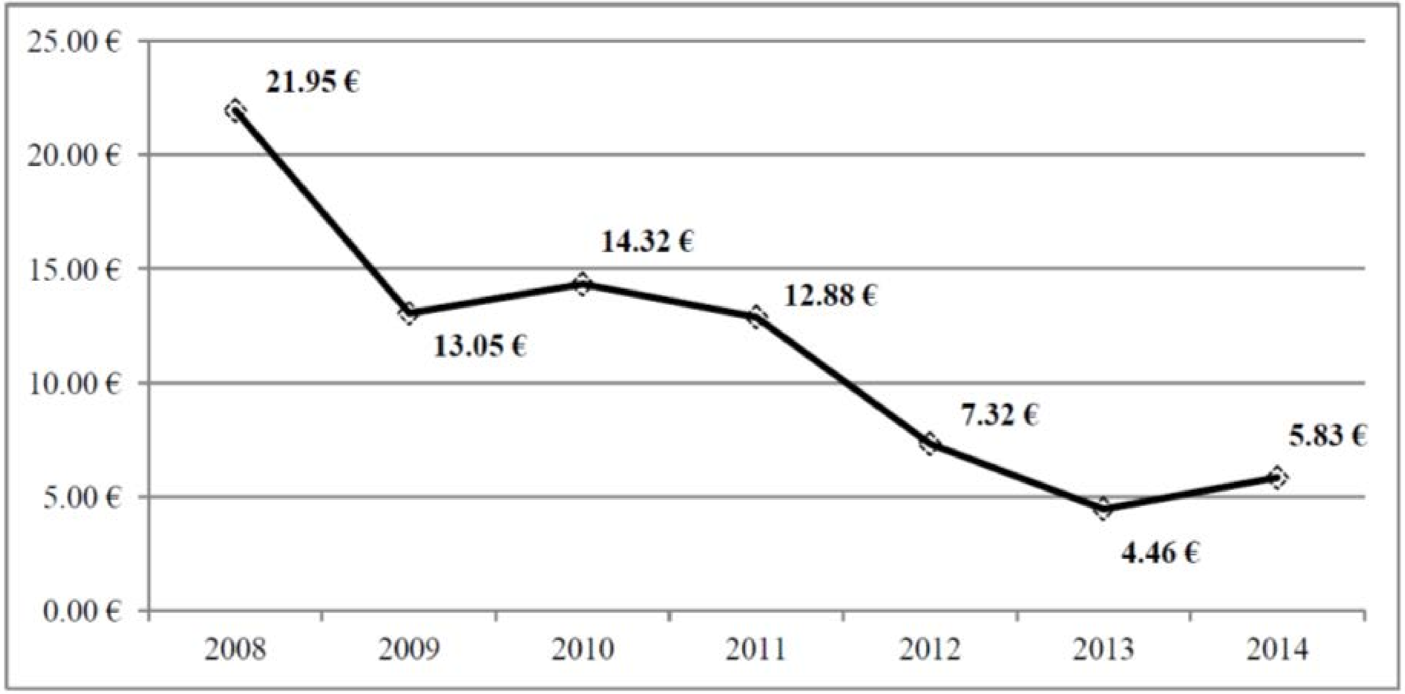
Cost of equivalent CO2 emissions:
European Union Emission Trading System



SSD Methodology

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STEP IV

Combination in Economic terms

kWh or m³ for energy (step I)
$kgCO_{2,eq}$ for environmental impacts (step II)
€ for structural costs (step III)

$$R_{E(energy)} = Q_E * P_E$$

Q_E *is the amount of energy consumption (in kWh or* m^3*)*
P_E *is the energy price (in €/kWh or €/* m^3*) provided by Eurost*

$$R_{E(CO_2)} = Q_{CO_2} * P_{CO_2}$$

Q_{CO_2} *is the amount of equivalent* CO_2 *(in kg or tonne)*
P_{CO_2} *is the carbon dioxide price (in* $€/kgCO_{2,eq}$ *or* $€/tonneCO_{2,eq}$*) provided by the European Union Emission Trading System (EU ETS)*

$$R_{SSD} = R_{E(energy)} + R_{E(CO_2)} + C_{tot}$$

C_{tot} *is the structural cost given by the sum of building initial costs and building losses*

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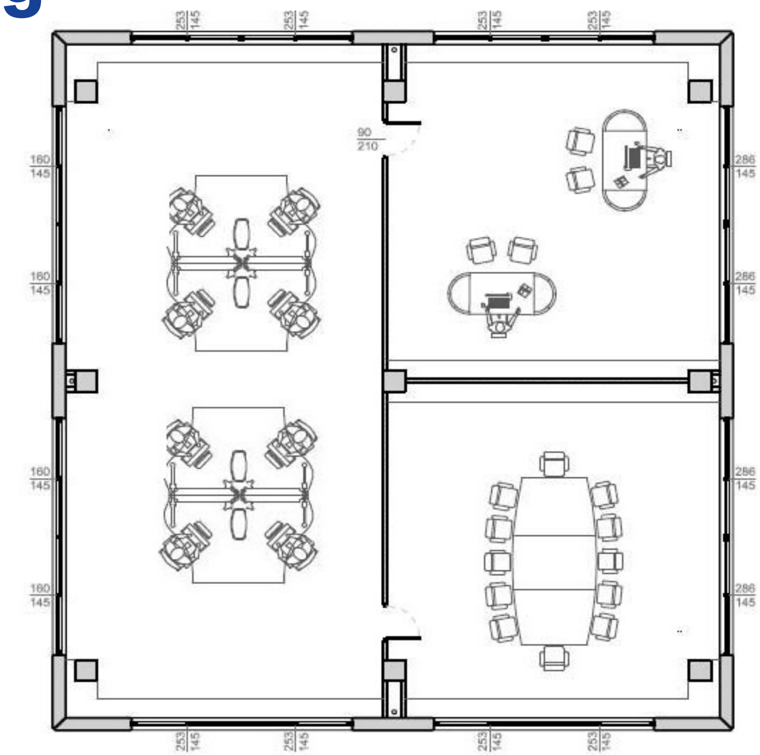
Application to a building



- Three storey building
- 15.62m × 16.87m in plan
- 2 spans of 7m in X and Y dir.
- 9.9m (3.5+3.2+3.2) height

Location: ***Barcis (PN)***

PGA = 0.25 g

Zone F → U = 0.26 W/m^{2}K

Office occupancy

Service life 50 years

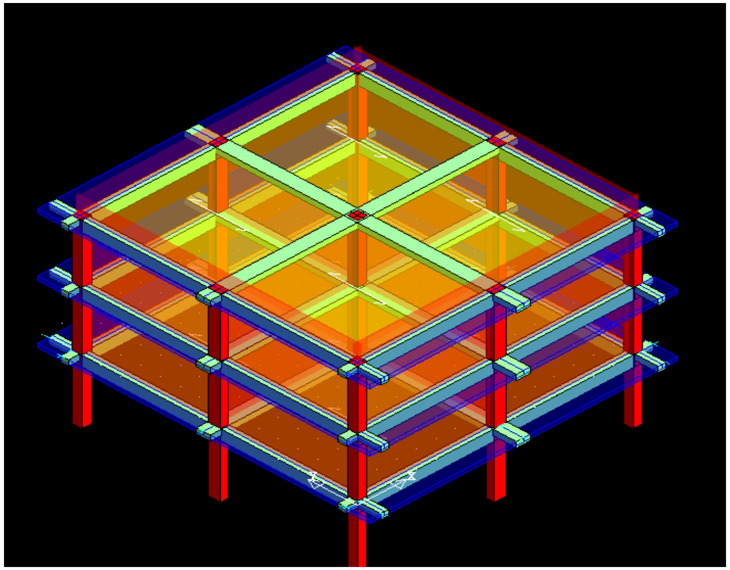
Application to a building

1) Precast Structure

- Real scale building
- Built and tested at ELSA (SAFECAST and SAFECLADDING)
- No walls, hinged connections

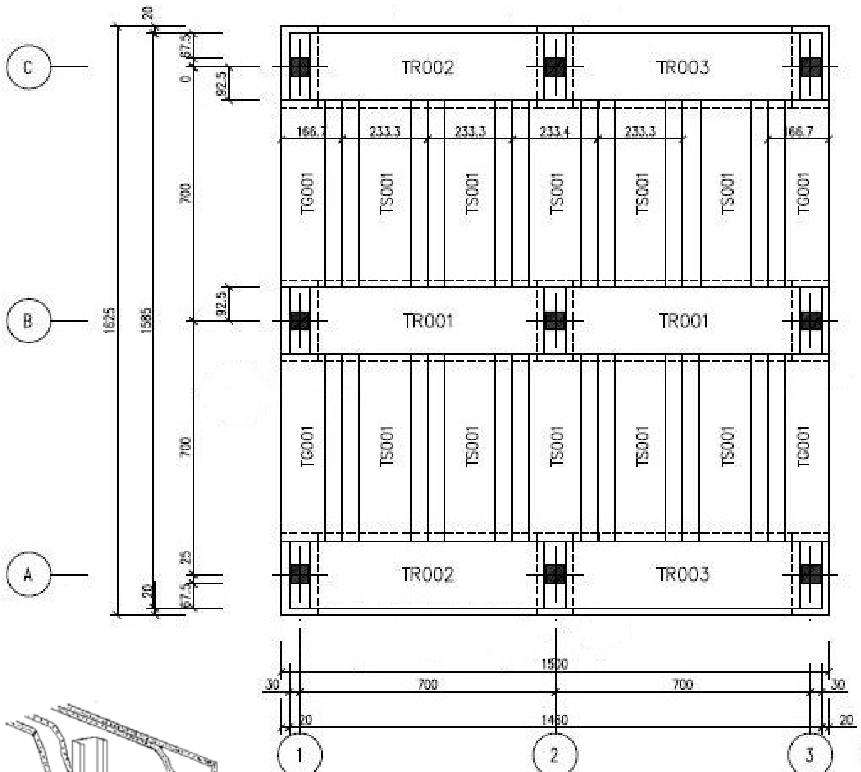
2) Cast-in-situ Structure

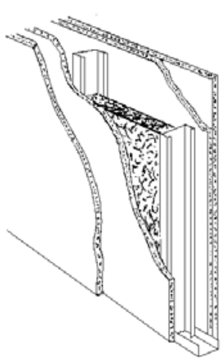
- Designed according to EC8
- Reinforced concrete structure
- Same architectural layout

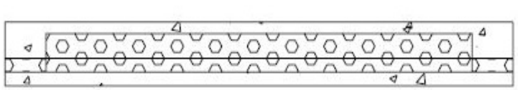


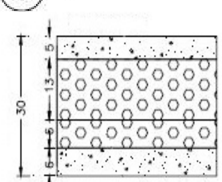
Application

1) Precast Structure

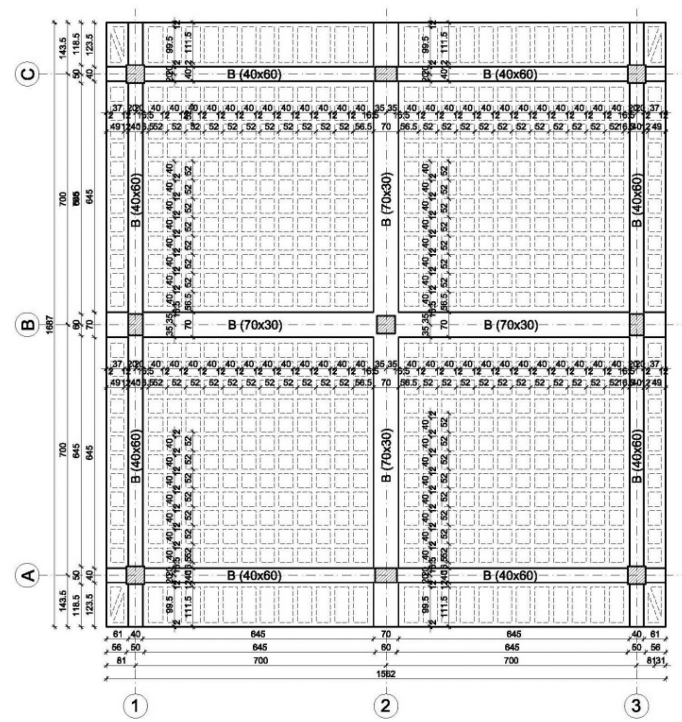


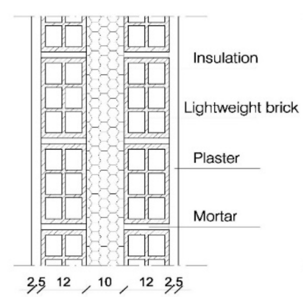


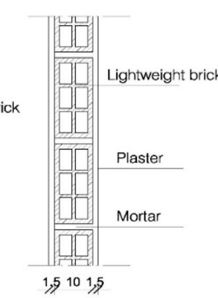




2) Cast-in-situ Structure







Life-Cycle Assessment

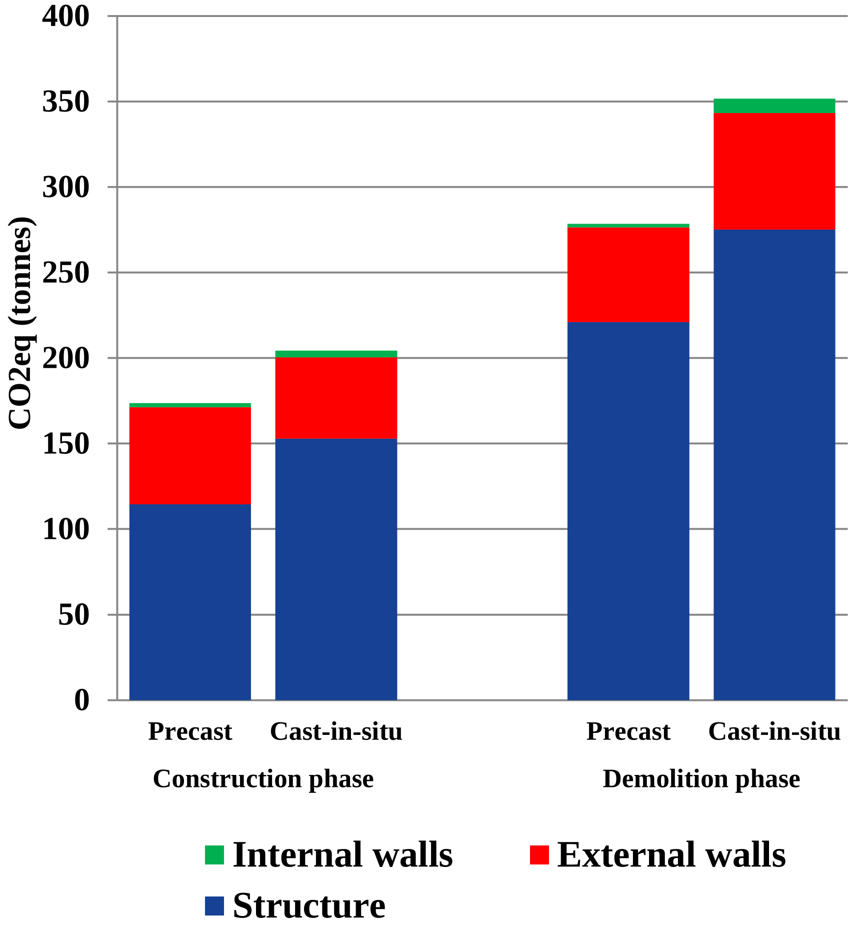
➢ *For construction and end-of-life phase*

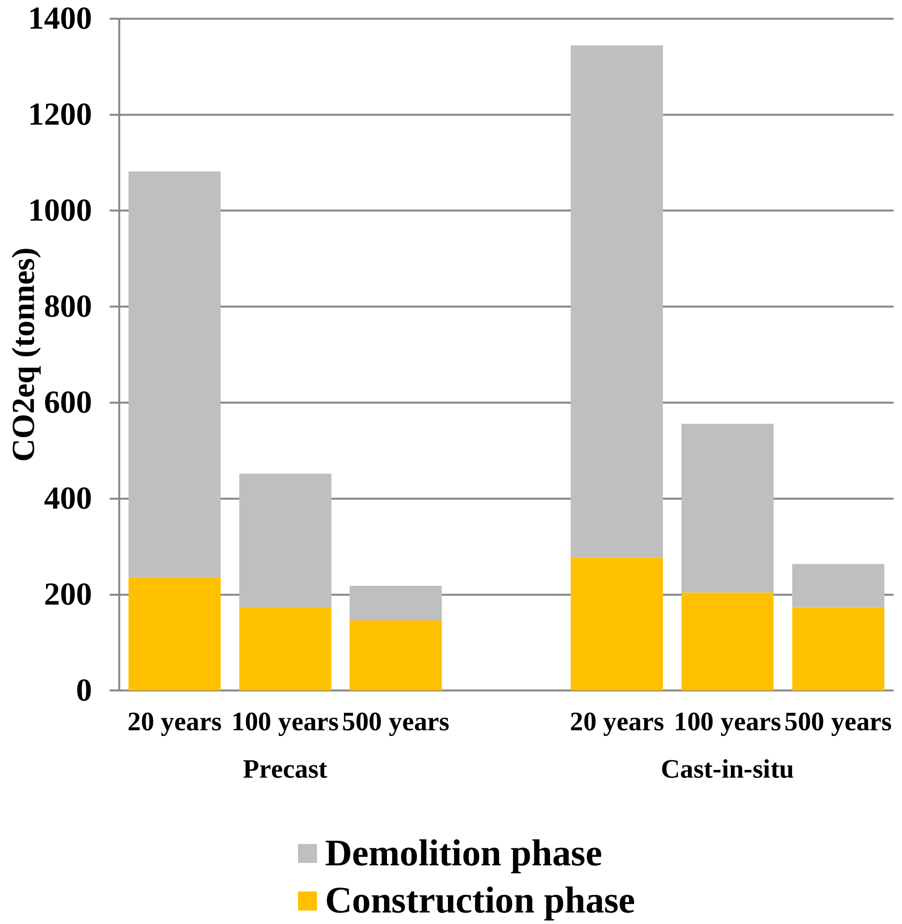
LCA → IPCC 2007 GWP 100a → SimaPro software

Precast	Material / process	Quantity	Unit	Construction	End-of-life	Total
				(ton CO_2eq)		
Structure	Concrete	177.3	m3	53.7		
	Steel	27.9	ton	40.8		
	Steel tendons	0.9	ton	0.9		
	EPS (slab)	1.4	ton	15.6		
	Transport	2800	km	2.2		
	Electricity	2300	kWh	1.3		
		Total structure		114.6	221.0	335.6
External walls	Concrete	44.0	m3	13.4		
	Steel	6.5	ton	9.5		
	EPS (panel)	2.9	ton	32.2		
	Transport	900	km	0.7		
	Electricity	1400	kWh	0.8		
		Total external walls		56.6	55.4	112.0
Internal walls	Gypsum board	3.2	ton	1.2		
	Rock wool	0.3	ton	0.3		
	Zink elements	0.6	ton	0.5		
	Transport	300	km	0.2		
	Electricity	500	kWh	0.3		
		Total internal walls		2.5	2.1	4.6
		TOTAL PRECAST		173.7	278.5	452.2

Cast-in-situ	Material / process	Quantity	Unit	Construction	End-of-life	Total
				(ton CO_2eq)		
Structure	Concrete	220.6	m3	66.7		
	Steel	29.2	ton	42.8		
	EPS (slab)	3.6	ton	40.0		
	Transport	2200	km	1.7		
	Electricity	2900	kWh	1.7		
		Total structure		152.9	275.0	427.9
External walls	Brick	59	ton	14.0		
	Mortar	32.5	ton	6.2		
	Plaster	45.2	ton	9.6		
	EPS (wall)	1.5	ton	16.7		
	Transport	500	km	0.4		
	Electricity	900	kWh	0.5		
		Total external walls		47.4	68.3	115.7
Internal walls	Brick	8.2	ton	2.0		
	Mortar	1.9	ton	0.4		
	Plaster	6.5	ton	1.4		
	Transport	250	km	0.2		
	Electricity	300	kWh	0.2		
		Total internal walls		4.1	8.3	12.3
		TOTAL CAST-IN-SITU		204.4	351.6	556.0

Life-Cycle Assessment





Energy Assessment

➢ *For operation phase*

Climatic zone F → ENEA → Italian national data for office occupancy

Electric consumption

ZONA CLIMATICA	INDICATORE [kWh/m² anno]
A	155
B	156
C	139
D	125
E	90
F	52

Heating consumption

ZONA CLIMATICA	INDICATORE [m³/m² anno]	INDICATORE [kWh/m² anno]
A	0,3	2,9
B	3,0	28,8
C	6,0	57,6
D	9,0	86,4
E	10,9	104,6
F	23,1	221,8

According Buildings Performance Institute Europe (BPIE) data: The annual average energy consumption in the non-residential sector is **280 kWh/m².**

Electricity: 52 kWh/m² year × (263,5 m² × 3)× 50 years = **2.055.300 kWh**

Gas: 23,1 m³/m² year × (263,5 m² × 3) × 50 years = **913.027 m³ gas**

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Structural Assessment

- **Initial Cost:**

Material Inventory from Environmental Assessment

- **Definition of Damage (Limit) States:**

Low damage: *start of the damage for non-structural elements*
Deformation (Maximum inter-storey drift) limitations according EC8:
- 0.5% for brittle non-structural elements attached to the structure (e.g. brick walls),
- 0.75% for ductile non-structural elements attached to the structure (e.g. concrete panels),
- 1.0% for non-structural elements not interfering with the structure (e.g. glass façade).

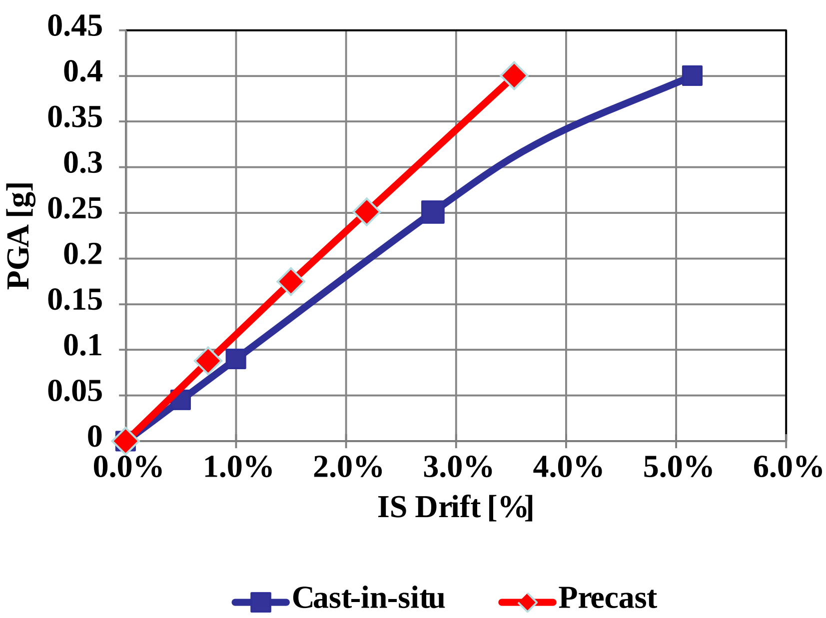
Heavy damage: *damage of all non-structural elements*
Maximum inter-story reaches goes twice the deformation limitations value.

Severe damage: *no-collapse requirement*
According EC8, the seismic action with 10 % probability of exceedance in 50 years i.e. with 475 years Return Period.

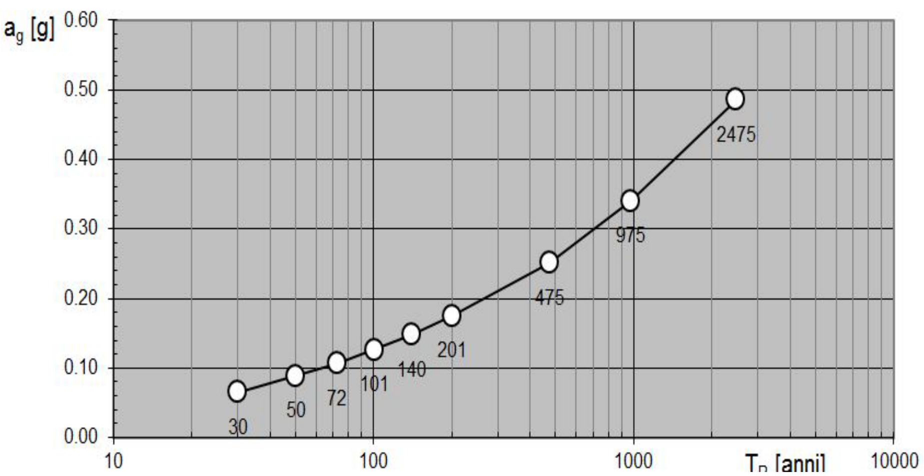
Near Collapse Limit State: *prevention of global collapse under a very rare event*
Full exploitation of the deformation capacity of structural elements.

Structural Assessment

Structural Analysis:



Hazard Analysis:



$$\log\left(a_g\right) = \log\left(a_{g1}\right) + \log\left(\frac{a_{g2}}{a_{g1}}\right) \cdot \log\left(\frac{T_R}{T_{R1}}\right) \cdot \left[\log\left(\frac{T_{R2}}{T_{R1}}\right)\right]^{-1}$$

$$R_N = 1 - \left(1 - \frac{1}{T_R}\right)^N$$

Structural Assessment

Cost Analysis:

Precast Structure						
Limit State	Drift [%]	PGA [g]	T_R [year]	R_{50} [%]	Damage cost [€]	Loss [€]
1	**0.75**	0.088	49.0	64.3	8318	3505
2	**1.50**	0.174	199.6	22.2	80216	9790
3	2.19	**0.250**	475.0	10.0	119743	8022
4	3.53	**0.400**	1489.5	3.3	988163	32631
					Total expected loss [€]	**53947**

Cast-in-situ Structure						
Limit State	Drift [%]	PGA [g]	T_R [year]	R_{50} [%]	Damage cost [€]	Loss [€]
1	**0.50**	0.045	30.0	81.6	9278	1750
2	**1.00**	0.090	51.1	62.8	92254	48692
3	2.79	**0.250**	475.0	10.0	148305	9935
4	5.15	**0.400**	1489.5	3.3	1008819	33313
					Total expected loss [€]	**93690**

Global Assessment Parameter

Environmental impact into monetary unit:

- **Carbon emissions:** (http://www.eex.com)
  - *Precast structure*

$$R_{E(CO_2)} = Q_{CO_2} \cdot P_{CO_2} = 452{,}2 \cdot 8{,}05 = 3.640€$$

  - *Cast-in-situ structure*

$$R_{E(CO_2)} = Q_{CO_2} \cdot P_{CO_2} = 556{,}0 \cdot 8{,}05 = 4.476€$$

- **Energy consumption:** (http://ec.europa.eu/eurostat)
  - *Electricity*

$$R_{E(kWh)} = Q_{(kWh)} \cdot P_{(kWh)} = 2.055.300 \cdot 0{,}174 = 357.622€$$

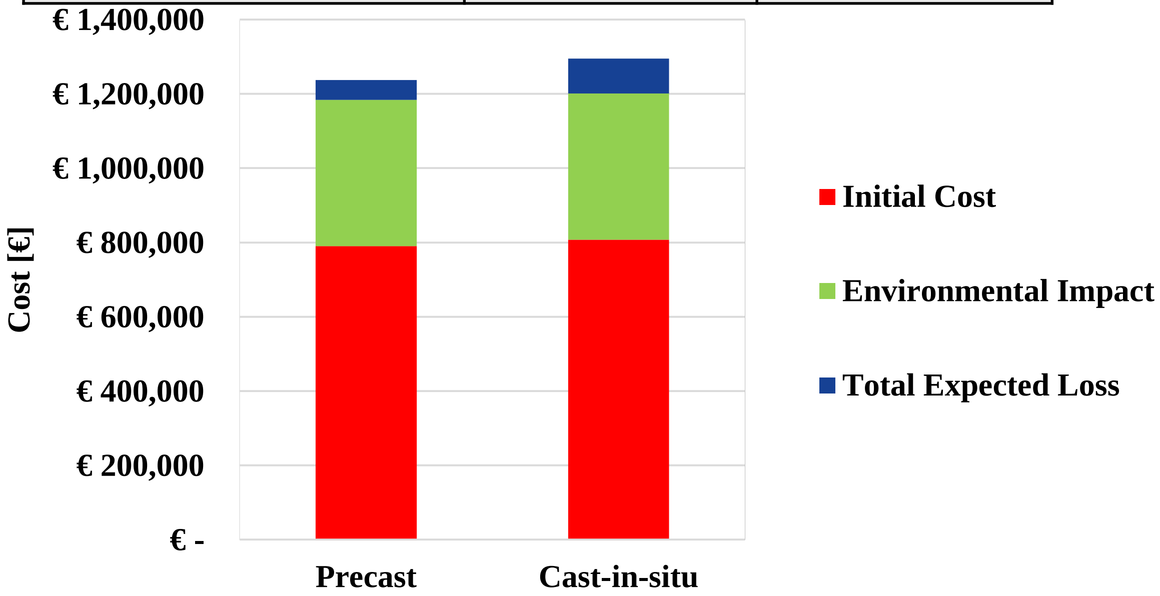
  - *Gas*

$$R_{E(gas)} = Q_{(gas)} \cdot P_{(gas)} = 913.027 \cdot 0{,}035 = 31.956€$$

- **Total**
  - *Precast structure* $R_E = 3.640 + 357.622 + 31.956 = 393.218€$
  - *Cast-in-situ structure* $R_E = 4.476 + 357.622 + 31.956 = 394.054€$

Global Assessment Parameter

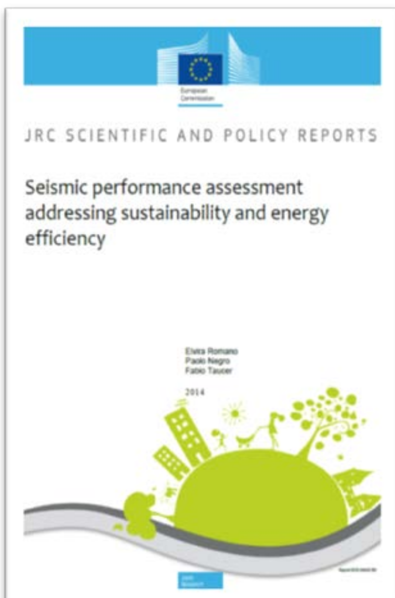
Cost [€]	Precast	Cast-in-situ
Initial Cost	790.530	807.055
Environmental Impact	393.218	394.054
Total Expected Loss	53.947	93.690
Global Assessment Parameter R_{SSD}	1.237.695	1.294.799

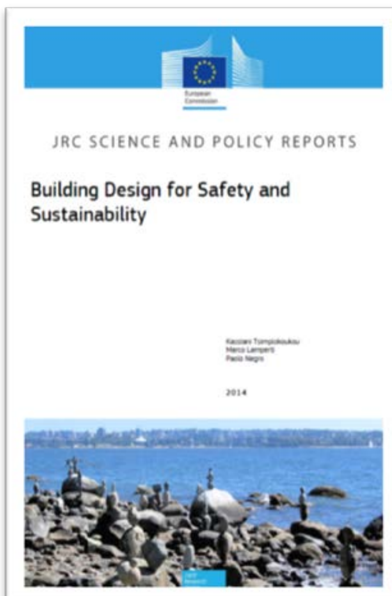


Conclusions (not yet)

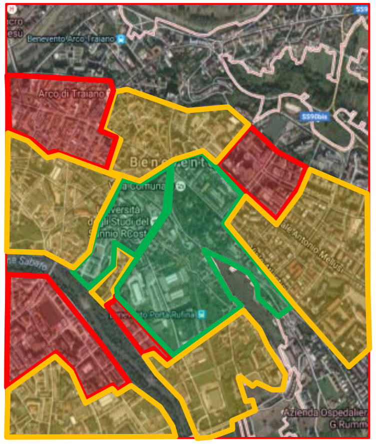
- Sustainable Structural Design (SSD) method considers both environmental and structural parameters in a life-cycle approach.
- SSD can be used to existing structures, as well as to new structures during design phase.
- Comparison between two cases is done on economic criteria. The effective solution is the one with the smallest value of $\mathbf{R_{SSD}}$.
- SSD involves diverse stakeholder categories to make decisions about design solutions in a multi-dimensional perspective.
- The environmental impact would become more important when $C0_2$ emissions would have reasonable market price.

SAFESUST: combining safety and energy efficiency.





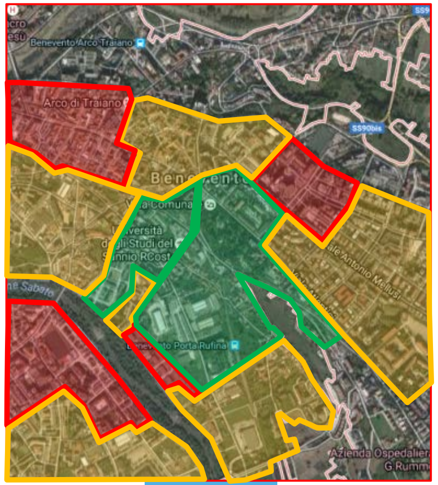
A single parameter to assess the performance of the intervention



Development of the SSD Methodology

The methodology can be used at urban/regional/national level for **supporting stakeholders** in addressing **policy projects on the territory**

Linking all the buildings of a defined territory to **a single parameter** leads to identifying the areas where an intervention is more **urgent** and would be more **efficient**



Not only earthquakes....

Structural safety

Higher live load requirements

Upgrading, transformations

Maintenance

Fire resistance

Damage to Ronan Point, 1968

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European Commission

Thank you for your kind attention! ☺

Joint Research Centre

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