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A Method To Include Life-Cycle Analysis In Earthquake Design

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Abstract

The construction industry, as a main energy consumer and a foremost contributor to greenhouse gas emissions, has been undergoing a "green revolution" in the recent years. Not occasionally, all recent directives and regulations of the European Union in the building sector dictate to design and construct structures in a balanced approach between economic, environmental and social aspects, enhancing sustainability and competitiveness of the sector.

Although the term of sustainable constructions is one of the most talked, current environmental impact assessment methods cannot be effectively used in the comparison of building solutions, as they do not include the structural performance of the building during its entire life. The presented Sustainable Structural Design (SSD) method considers both environmental and structural parameters in a life cycle perspective. The integration of environmental data in the structural performance is the focus of the method. Structural performances are considered in a probabilistic approach, through the introduction of a simplified Performance Based Assessment method.

The SSD method is implemented in a case study of an office occupancy building both for precast and cast-in-situ structural systems to find, for the case at hand, the best solution in terms of both sustainability and structural performance.

Keywords: Sustainable Structural Design; Environmental Assessment; Performance-Based Design.

1. Introduction

Sustainable development is a fundamental objective of the European Union. Its strategy constitutes a long-term vision and an overarching policy framework providing guidance for the EU targets with a timeframe of up to 2050. The intensified ongoing work of the Commission tends to merge the policies for economic, social and environmental development in order to afford the higher demand for materials and energy [1].

The European construction sector plays a significant role as one of the main contributors of the European economy and job market. On the other hand, it has also large impact on the environment due to greenhouse gas emissions and energy consumption. For this reason the European target, pursed with several initiatives and action plans, is to develop the market of sustainable constructions. The structure at the same time has to satisfy several requirements related to the environment, society and economy parallel with requirements of structural design. Moreover, all these requirements should be guaranteed during the *Life Cycle* (LC) of the structure [2].

To reach all the targets stated above, a new avant-garde way to conceive structures is needed. The design process should concern the whole LC of structures and their components, in order to reduce environmental impacts and increase the durability of structures. In this light, the *Sustainable Structural Design* (SSD) method hereinafter presented could be the solution to design constructions, considering all buildings requirements in a holistic way [2]. First, the theoretical background of the SSD method is explained in details, afterwards, the application of the method to a case study is presented. A three-storey RC building is designed with two different solutions (precast and cast-in-situ) in order to compare both sustainability and structural performance.

2. Sustainable Structural Design (SSD) method

The *SSD method* is conceived as a supporting tool for the building design process. It takes into account technical-structural aspects along with environmental ones during the entire LC. It tends to optimize the building design in terms of *structural* and *environmental* performance, configuring a design method both for *safety* and *sustainability* [3].

2.1. Framework of the SSD method

The framework of the SSD method, shown in figure 1, is based on three main pillars: *environmental*, *structural* and *economic* assessment. The following sections will describe each of these components in detail.

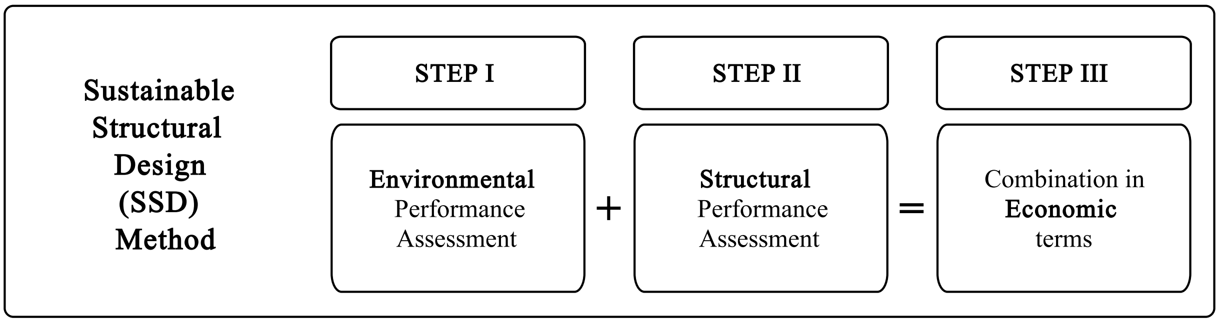


Fig. 1 – Steps of the SSD method [2]

2.2. Environmental Assessment

2.2.1. Importance of environment assessment in the construction sector

The construction industry is a major material and energy consumer and thus a significant contributor to environmental burdens like climate change and global warming [4]. The global climate change is caused from the concentrations of *greenhouse gases* (GHG) such as *carbon dioxide* (CO_2), methane and nitrous oxide in atmosphere with building sector being responsible for 33% of them [5]. Further studies indicate that the greatest impacts on human health and toxic releases occur during the manufacturing and construction phase, while the greatest amounts of energy consumption (70-90%) and GHG emissions result during the operation phase [6].

As a result, the 2012/31/EU directive of 2012 stated that the focus of the building and construction sector should be in energy efficiency [7]. For this reason, improving the energy performance of buildings is an essential measure in order to achieve the ambitions of Europe, specifically the *EU Climate & Energy targets*, which refer to the reduction of greenhouse gas emissions by 20% and energy savings of 20%, both by 2020 [8].

Moreover, climate change and global warming are not concepts that touch only specific countries or continents but they are worldwide issues. The first international effort against the climate change was paid off by the signature of Kyoto Protocol. After 20 years of UN negotiations, a binding and universal agreement on climate was signed from all the nations of the world during Paris Climate Change Conference in 2015 [9].

2.2.2. Life Cycle Assessment (LCA) method

The first step of the SSD method deals with environmental evaluation of products and processes throughout the entire building life. The results of analysis are obtained using *Life Cycle Assessment* (LCA) method that is a multi-step procedure for analyzing environmental burden of products and processes [9].

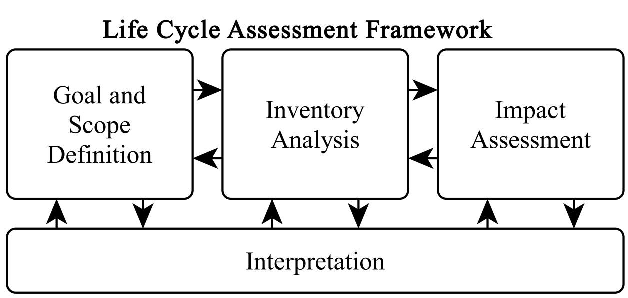


Fig. 2 – Steps of the LCA method according to ISO 14040 [11]

The general procedure for conducting a LCA is defined by the International Organization for Standards (ISO) series ISO 14040 [11] and ISO 14044 [12]. According to their guidelines, the LCA method is composed in four steps that are goal, scope and boundary definition; life-cycle inventory (LCI) analysis; life-cycle impact assessment (LCIA) and interpretation of results (Figure 2).

LCA method has been used to evaluate the environmental impact of many industries for a long time but in the construction sector, its application is still considered innovative [10]. The method is also known as cradle-to-grave analysis as it takes into account all phases of building life from raw material extraction, manufacture, transportation, use, maintenance, and end-of-life via disposal or recycling [13], see Figure 3 below.

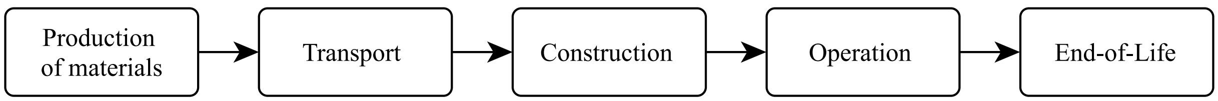


Fig. 3 – Flowchart of the LCA of a building

The most appropriate way to assess the environmental impact of a building is to evaluate its performance with an energy approach. In the SSD method, this is achieved by applying the *Life Cycle Energy Analysis* (LCEA), accounting all energy inputs to a building in its LC. The system boundaries of this analysis include the total energy used for the three main phases of the building life: *construction*, *use* and *demolition* [14]. The *LCEA* determines:

- *Embodied energy*

E_E represents the energy required for *extracting*, *manufacturing* and *transporting* all the materials used in the building, and energy incurred at the time of the *construction* or *renovation* of the building. E_E is expressed as:

$$E_E = \Sigma\, m_i \cdot M_i + E_T + E_C \tag{1}$$

where:

m_i is the material quantity;
M_i is the energy content needed for the production/extraction of material unit quantity;
E_T is the energy consumed for the transportation of materials to construction site;
E_C is the energy used at site during the construction.

- *Operating energy*

E_O represents the energy required for maintaining comfort conditions and day-to-day maintenance of the buildings. It is the energy needed for HVAC (*heating*, *ventilation* and *air conditioning*), domestic *hot water*, *lighting*, and running *appliances*. E_O throughout the lifespan of the building is expressed as:

$$E_O = E_{OA} \cdot L_b \tag{2}$$

where:

E_{OA} is the annual operating energy;
L_b is the life span of the building.

- *Demolition (End-of-Life) energy*

E_D represents the energy required at the end of the building life to *demolish* it and to *transport* the material to *landfill* sites or *recycling* plants. E_D is expressed as:

$$E_D = E_{DIS} + E_{T'} \tag{3}$$

where:

E_{DIS} is the energy used during the demolition/dismantling process;
$E_{T'}$ is the energy consumed for the transportation of materials to landfill/recycling sites.

In the end, the total energy over the entire life of the building is the sum of energy incurred at each phase of its life. Therefore, the *life cycle* energy E_{LC} is expressed as:

$$E_{LC} = E_E + E_O + E_D \tag{4}$$

After performing *LCEA*, phases that demand high amount of energy can be determined and further studies can be done from specialists of various fields in order to reduce energy consumption and improve building qualities.

2.3 Structural Performance-Based Assessment

The second step of the SSD method deals with the structural design using a *Performance-Based Assessment* (PBA). The design should not be seen as the sole aspect of structural response but also in the aspect of structural performance [15]. This is expressed as predefined design targets that structures need to meet over their life [16].

The structural PBA implements probabilistic scenarios that can occur during the lifespan of the structure [17]. Therefore, not only loads imposed on the structure but also uncertainty and probabilistic response should be taken into account in the analysis [18]. The *uncertainties* are grouped into three main categories namely *hazard* uncertainty (e.g. *earthquake*, *wind*), *structural* uncertainty (e.g. *material properties*) and *interaction mechanism* uncertainty (e.g. *pressure duration*) [17]. The PBA allows structural systems to be designed to meet performance targets: *capacity*, *safety* and *quality*. The final results of structural PBA are presented in economic context, by evaluating all the costs associated with a structural solution, as well as the expected losses that may occur to the building during its life. Afterwards, the specialists can evaluate and make decisions between alternative design or retrofitting solutions [16].

2.3.1 Simplified Performance-Based Assessment (sPBA) method

The development of PBA methods is gaining big interest in the field of structural engineering. This interest originates from the successful implementation of the Performance-Based Earthquake Engineering (PBEE) method from the Pacific Earthquake Engineering Research (PEER) Center [19]. The PEER's PBEE method has been fundamental in addressing the importance of integrating loss-assessment within structural design. However, such method seems too complicated to be applied to ordinary projects, due to complex probabilistic relations.

Considering the latter, a *simplified Performance-Based Assessment* (sPBA) has been introduced by the European Commission's Joint Research Centre (JRC) - European Laboratory of Structural Assessment (ELSA) [20]. The framework of the sPBA aims at reducing the complexity and the amount of data needed as well as at simplifying the procedure of estimating losses due to uncertainties. The output of the analysis determines the cost the structure together with expected losses for each defined limit state, corresponding to different *peak ground accelerations* (PGAs) and *inter-storey drift ratios* (IDRs) [2]. The steps of the sPBA method are as follows:

- *Limit States Definition*

The limit states are defined in terms of damageability and the expected costs for each limit state are calculated. The damage (limit) states that can be defined in a building are low damage, heavy damage, severe structural damage and loss of the building/collapse. The *Engineering Demand Parameter* (EDP) that measures the structural damage is the IDR, thus the IDR values are calculated for each damage level by using fragility curves.

- *Structural Analysis*

The structural analysis step consists in the calculation of PGAs that cause the IDR values defined in the previous step. This correlation is defined through skeleton curves that are obtained from the Incremental Dynamic Analysis (IDA) of the FEMA-350 guidelines [2], or simply from a standard push-over analysis. After performing this analysis to a structural system, the PGA versus IDR can be defined for each damage state configuration.

- *Hazard Analysis*

In the hazard analysis, the output of the structural analysis is used to estimate the probability of exceedance. Modern seismic codes provide the relation between the return periods (T_R) and the PGAs. For example, the Italian seismic code [21] provides a set of values of peak ground accelerations for nine return periods (30, 50, 72, 101, 240, 201, 475, 975 and 2475 years) along with the interpolation formula for values in between.

$$\log(a_g)=\log(a_{g1})+\log\left(\frac{a_{g2}}{a_{g1}}\right)\cdot\log\left(\frac{T_R}{T_{R1}}\right)\cdot\left[\log\left(\frac{T_{R2}}{T_{R1}}\right)\right]^{-1} \tag{5}$$

where:

a_g is the PGA calculated for a defined damage state;
T_R is the return period which corresponds to that state;
a_{gi} are the intermediary values of PGA taken from the seismic map;
T_{Ri} are the return periods corresponding to a_{gi}.

After determining a_g values from the previous step, the return period T_R can be defined for each damage state. Therefore, the probability of exceeding R_N in N years is expressed from the following equation [21]:

$$R_N = 1 - \left(1 - \frac{1}{T_R}\right)^N \tag{6}$$

- *Cost Analysis*

The total cost of the building is the sum of the initial construction cost and the expected total loss over the project LC. While the initial cost includes the expenses related to the initial establishment of the facility, the estimation of expected total loss is more complex and involves different stakeholder categories [3].

More specifically, firstly, the contractor estimates the time needed to repair the damages of each limit state. This information about time needed for each limit state is associated with the downtime loss. Downtime refers to the period of time in which the system fails to provide its primary function and therefore downtime loss expresses the amount of money that will be spent (lost) while the building is not used. Later, for each state, the structural engineer calculates the cost of repair of the damages [3].

Therefore, the expected loss for each limit state is expressed as the sum of monetary loss (the amount of money needed to repair the damaged building) and downtime loss (the amount of money spent during the repairing actions e.g. for rent, removal, etc.). The latter is expressed in the following equation:

$$C_i = E\left(Loss_{repair} | IM\right) + E\left(Loss_{downtime} | IM\right) \tag{7}$$

Once the costs C_i are determined for each limit state and the respective probabilities of exceedance R_i have been calculated, the total expected loss can be estimated via the total probability theorem as follows:

$$L = \sum_{i=1} C_i \cdot \left(R_i - R_{i+1}\right) \tag{8}$$

Thus the total cost of the building C_{TOT} is expressed as the sum of initial construction cost and the total expected loss as follows:

$$C_{TOT} = I + L \tag{9}$$

where:

I is the initial construction cost;

L is the total expected loss needed to repair a damaged structure.

Once the analyses are performed for two or more structural design solutions, the evaluation can be done based on economic criteria. This means that the most effective solution is the one with the smallest value of total cost, even if it has higher initial cost but requires less repair and downtime costs during the building lifetime.

2.4 Global Assessment Parameter of the SSD method

The third step of the SSD method is the combination of environmental and structural results. To achieve this, the method aims at addressing a *Global Assessment Parameter* (GAP) that is the sum of environmental and structural assessment results expressed in economic terms [3]. While for structural performance-based assessment the results are already expressed in monetary unit, the environmental assessment results are obtained in terms of energy. Therefore, firstly the environmental impact needs to be converted into economic terms and afterwards, the GAP of SSD method can be determined.

2.4.1 Environmental performance into monetary unit

Until today in Europe there are market prices only for the CO_2, therefore only the environmental impacts associated with the global warming potential (carbon footprint) can be converted into costs [3]. In general, the results of the environmental performance of buildings are determined in terms of carbon footprint and embodied energy consumption during the entire lifespan. Carbon footprint is defined as the total amount of GHG emissions caused by building LC phases, expressed in equivalent tonnes of carbon dioxide ($CO_{2\text{eq}}$). Meanwhile, the embodied energy includes the energy consumed by processes associated with the production, use and demolition of the building, expressed in *megajoule* [*MJ*], *kilowatt-hour* [*kWh*] or cubic meters of natural gas [m^3] [22]. The conversion of the results into monetary unit can be done for each category following the EU directives:

- *Carbon dioxide (CO_2) emissions*

The CO_2 price per tonne is linked with the *EU Emissions Trading System* (EU ETS). According the EU ETS, each member state agrees on maximum national emission limit that should be approved by the *European Commission* (EC). Then the Union countries allocate allowance values to their industrial operators, who are able to buy or sell such allowances named *European Emission Allowances* (EUA) [23]. The total number of permits issued, either auctioned or allocated, defines the price per carbon which is therefore, determined by stock exchange rules. Considering the carbon prices deriving from EU ETS, the monetary cost of the environmental impact referring carbon footprint $R_{E(CO2)}$ can be expressed as follows:

$$R_{E(CO_2)} = Q_{(CO_2)} \cdot P_{(CO_2)} \tag{10}$$

where:

Q_{CO2} is the amount of the CO_{2eq} emissions calculated from the analysis [*tonne*],

P_{CO2} is the price of one tonne CO_2 according to the *EUA* [*€/tonne*].

- *Energy consumption*

The price for gas and electricity can be determined using the *Eurostat* data [24] for each member state or the average price of all the EU in the household or industrial category. Therefore the total energy price $R_{E(Energy)}$ can be calculated for a specific country or using the average price by the following equation:

$$R_{E(Energy)} = Q_{(Energy)} \cdot P_{(Energy)} \tag{11}$$

where:

Q_{Energy} is the amount of the energy consumption [*kWh* or m^3 gas],

P_{Energy} is the price of one *kWh* or m^3 of gas [*€/kWh* or *€/*m^3 gas].

2.4.2 Equation of the Global Assessment Parameter (R_{SSD})

After converting environmental impacts into monetary unit, the GAP R_{SSD} of Sustainable Structural Design method can be expressed as the total sum of environmental and structural impact as follows:

$$R_{SSD} = R_{E(CO_2)} + R_{E(Energy)} + C_{TOT} \tag{12}$$

3. Example of application

Sustainable Structural Design method was applied to a three-storey building of commercial (office) occupancy. Two different structural systems for the building were conceived. Firstly, it was designed as a precast reinforced concrete structure and afterwards to its equivalent cast-in-situ in order to find the best solution in terms of environmental and structural aspects.

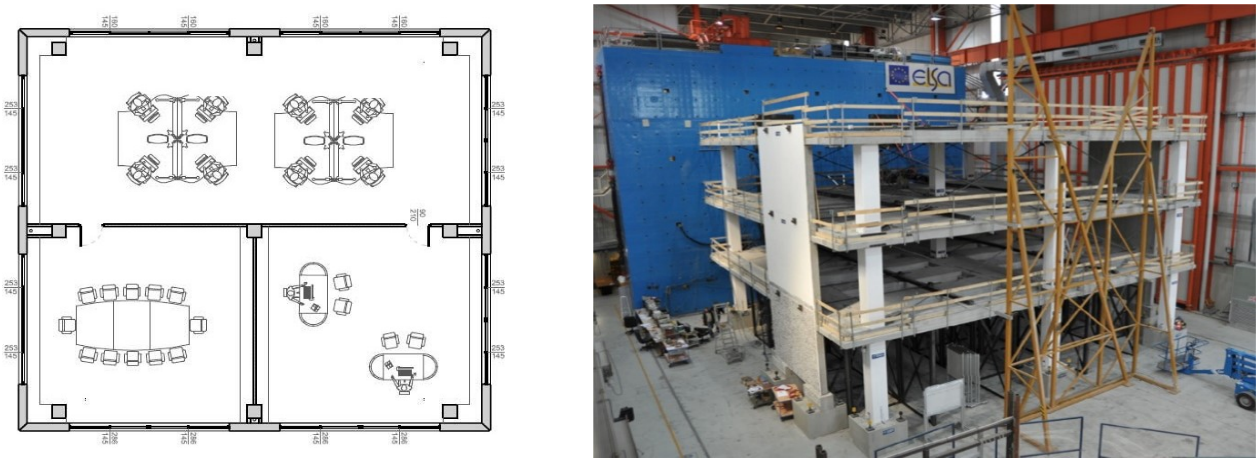
3.1. Description of the building

The building is 15.62 × 16.87 *m* in plan with two 7 *m* spans in both directions. The total height of the structure is 9.9 *m* with floor heights equal to 3.5 *m* for the first floor and 3.2 *m* for both second and third floor.

Both precast and its equivalent cast-in-situ structures were designed according to Eurocode 8 [25] prescriptions to withstand the same vertical and horizontal load. The location of the building is considered in the Comune of Barcis (PN) in Friuli-Venezia Giulia region. Seismicity data are taken from the seismic map of Italy [21] that corresponds to a peak ground acceleration of 0.25 *g* for a 475 *years* return period. The material properties and loads acting on both structures are shown in Table 1.

Table 1 – Material properties and design loads on the structures

Structures features	**Material properties** [N/mm2]			**Vertical loads** [kN/m2]		**Seismic load** (Soil type B)	
	Concrete	Steel	Tendons	Imposed	Live	PGA	Behaviour factor
	R_{ck}	f_{yk}	f_{ptk}	q	p	a_g	q
Precast	55	450	1860	0.5	2.0	0.25	3.00
Cast-in-situ	37	450	-	0.5	2.0	0.25	3.63



(a) General plan of the structure (b) View of the experimental precast build. [26]

Fig. 4 – Building and model

3.1.2. Precast structure

The first structure is a precast reinforced concrete structure that was mocked up and tested at the European Laboratory of Structural Assessment (ELSA) as part of the SAFECAST project [26]. The external façade is also conceived as a precast solution with concrete panels attached to the structure. An overview of the experimental set up is shown in Figure 4b.

The structure represents the most common connection system in the European precast construction practice with hinged beam-column connections. The skeleton has dimensions in plan 15.0 × 16.25 *m* with precast panels of thickness 0.30 *m* attached to the perimeter. The cross section of the columns is 0.5 × 0.5 *m* and, in correspondence to the storeys, they have a capital with maximum width of 2.25 *m*, on which the hinged beam-column connection is realized. The beams are box elements with maximum width of 2.25 *m* and prefabricated floor systems have been used.

The prefabricated concrete panels of the external façade are selected from the manual "*Pannelli prefabbricati in calcestruzzo – Linee Guida*" ("Precast concrete panels – Guidelines") of the Italian association of precast producers (ASSOBETON) [27]. According to the Italian climatic map, the building is situated in climatic zone *F* which corresponds to a minimum thermal transmittance U = 0.26 W/m^2K [28]. Therefore, the selected panel is the type 2 with thermal transmittance U = 0.259 W/m^2K. To divide the compartments inside the floor, the partition walls are considered of double gypsum board with thickness of 10 *mm* and acoustic insulation of rock wool in between.

3.1.2. Cast-in-situ structure

The cast-in-situ structure was designed with the same loads and dimensions as the precast structure, using professional software SAP2000 [29].

The central and corner columns have dimensions 0.5 × 0.5 *m* while the other ones are 0.8 × 0.4 *m*. The beams dimensions are 0.7 × 0.3 *m* for the internal frames and 0.4 × 0.6 *m* for the external ones. The slab is designed as continuous two-way ribbed slab with total height 0.30 *m* and thickness of topping 50 *mm*. The width of the ribs is 0.12 *m* while their axial distance is 0.52 *m*. The distance between the ribs is filled with expanded polystyrene (EPS) to have similar slab self-weight as the precast structure (self-weight of the ribbed slab is 3.8 kN/m^2 while self-weight of the precast slab is 3.7 kN/m^2).

The walling system of the cast-in-situ structure is made of masonry brickwork. The external walls are composed of two parallel lightweight brick walls with thickness of 120 *mm* each and 100 *mm* of insulation (EPS) in between. On both sides of the walls is applied 25 *mm* of plaster making the thermal transmittance of the wall configuration U = 0.257 W/m^2K. The internal divisions are also made of lightweight brick walls of thickness 80 m*m* with two plaster layers of 15 *mm* applied on both sides.

3.2. Environmental Assessment

The comparison of the environmental impact of the two buildings has been performed only for the products and processes that are different in the two cases. More specifically, the analyses have been performed for the structural and walling systems as the only components of the buildings that are different in the configurations. The other building elements like windows, flooring tiles, installations, etc., are considered the same in both buildings so they do not influence in the comparison result. Following the same logic, as external walls are selected with similar thermal transmittance, the amount of energy needed for HVAC (heating, ventilation and air conditioning), lighting, domestic appliances, etc., will be the same for both buildings. Therefore, operating energy will be calculated using an average value for office occupancy during the entire life of the building.

The LCA results for construction and demolition phases have been carried out with the help of the software SimaPro [30]. The software includes several inventory libraries and databases that makes it a very practical tool for measuring the environmental impacts of products and services during all LC stages. The selected method for assessing the environmental impact of the buildings is IPCC 2007 [31]. This method is developed by the International Panel on Climate Change (IPCC) and it is characterized by a system of equivalent factors to weight the influence of various GHG, using the amount of CO_2 as reference. It lists the Global Warming Potential (GWP) of well-mixed GHG commonly for time horizon of 20, 100 and 500 *years*. GWP depends on the timespan over which the potential is calculated as the gas concentration decays over time in the atmosphere. In this study, the results have been carried out for the timeframe of 100 *years* as the most recommended time horizon for such analyses.

The system boundaries include construction phase (extraction, manufacture and transport of materials) and end-of-life phase via disposal of all the material to landfill. The emissions expressed in equivalent tonnes of CO_2 for construction and end-of-life phases are given in Table 2.

Table 2 – Comparison of carbon footprint for both structure solutions

Carbon footprint	Precast			Cast-in-situ		
[*ton* CO_2eq]	**Construction**	**End-of-life**	**Total**	**Construction**	**End-of-life**	**Total**
Structure	114.6	13.3	127.9	152.9	21.9	174.8
External walls	56.6	11.3	67.9	47.4	6.4	53.8
Internal walls	2.5	0.0	2.5	4.1	0.2	4.3
Total	173.7	24.6	**198.3**	204.4	28.5	**232.9**

Diagrams in Figure 11 show the environmental impact for each analyzed component of the buildings during construction and end-of-life phases. As one can see, the greenhouse gas emissions of the cast-in-situ structure are higher for both construction and demolition phases.

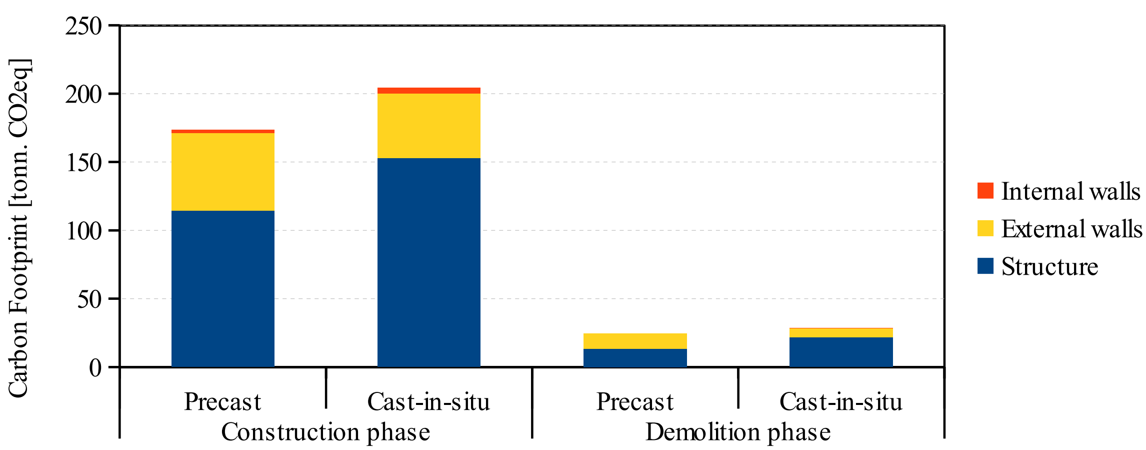


Fig. 5 – Comparison of gas emissions for both buildings

In order to complete the environmental assessment, energy needed during the use phase must be determined. The energy of the operation phase will be estimated in terms of electricity and gas consumed during the entire life of the structure as the most popular sources of energy used in HVAC systems. The value of energy needed will be assumed the same as the thermal transmittances of external walls and windows are similar in both cases.

- *Electricity consumption*

The annual electric energy consumed for office occupancy buildings per square meter in the climatic zone F is 52 $kWh/m^2 \times year$, as reported by Italian Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) [32], the annual electric energy consumed for office occupancy buildings per square meter in the climatic zone F is 52 $kWh/m^2 \times year$. The electric energy consumed in 50 years of building LC is: $E_{(kWh)} = 52\ kWh/m^2\ year \times (263.5\ m^2 \times 3) \times 50\ years = 2'055'300\ kWh$.

- *Heating consumption*

The report also indicates the annual quantity of electricity or natural gas consumed for heating in office buildings situated in climacteric zone F that is 221.8 $kWh/m^2 \times year$ or 23.1 $m^3/m^2 \times year$. Total electricity consumption for all purposes (273.8 $kWh/m^2 \times year$) is very similar to the EU average specific energy consumption in the non-residential sector given by Buildings Performance Institute Europe (BPIE) that is 280 $kWh/m^2 \times year$ [33]. The source of energy used for heating purposes in the application is natural gas. The amount of gas consumed in 50 *years* is: $E_{(gas)} = 23.1\ m^3/m^2\ year \times (263.5\ m^2 \times 3) \times 50\ years = 913'028\ m^3\ gas$

3.3. Simplified Performance-Based Assessment

The first step of the sPBA method is the evaluation of initial construction cost for each design solution. The unit price for each material is taken from the price list manual of construction works issued by Commerce Chamber of Milano [34]. The prices of other components of the buildings, that are the same in both typologies (windows, tiles, installations, etc.), are defined with a simplified price approach for meter square.

Afterwards, the second step of the method is the definition of limit states and the evaluation of expected losses that may occur over the life span of the buildings for each state. Four limit states are defined with different situations of damage as follows:

Low damage: the damage begins for non-structural elements. The first non-structural elements that face damage are considered the external walls parallel to seismic direction including windows in the story with maximum IDR. Repair cost includes the cost of demolition and construction of these walls and replacement of the windows. The definition of this state is done based on the following deformation limitations according to Eurocode 8 (Maximum IDR due to the “frequent” earthquake):

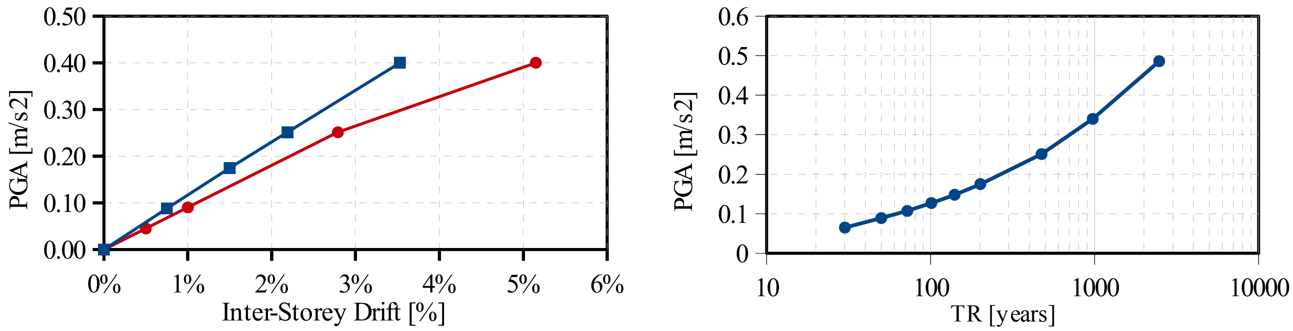
- 0.5% for brittle non-structural elements attached to the structure (e.g. brick walls);
- 0.75% for ductile non-structural elements attached to the structure (e.g. concrete panels);
- 1.0% for non-structural elements not interfering with the structure (e.g. glass façade).

Heavy damage: damage of all non-structural elements. All non-structural elements (walls and windows) are damaged and they need repair works meanwhile the structure does not need intervention. Damage cost includes demolition and reconstruction of all walls and replacement of the windows. This limit state is considered to occur when the maximum IDR reaches twice the deformation limitation value.

Severe damage: no-collapse requirement. All non-structural elements needs to be replaced (limit state 2) and structural beams of first floor parallel to the seismic direction need retrofit due to the creation of plastic hinges. According Eurocode 8, no-collapse requirement for ordinary structures is met for a reference seismic action with 10 % probability of exceedance in 50 years (recommended value) i.e. with 475 years Return Period. The damage cost of this state includes the cost of the previous step and the retrofit cost for the damaged beams. No discontinuity of activity in the building is considered.

Near Collapse (NC) Limit State: prevention of global collapse under a very rare event (1500 to 2000 years return period). This state corresponds to the full exploitation of the deformation capacity of structural elements. According Eurocode 8, this design verification is needed to reduce the uncertainty and promote a good behaviour of the structure, even under earthquakes more severe than the design seismic action. The total damage cost of this state includes cost of demolition, reconstruction of new building and payment of day-off for a period of 12 months (time of construction).

For the precast structure, the relationship between PGA and IDR values is determined using skeleton curves deriving from laboratory tests [35]. Meanwhile for the cast-in-situ structure, the relationship is obtained by running pushover analysis in the software SAP2000. Figure 13 shows the relation between PGA values and IDR for both typologies of structures. For the obtained PGA values, the corresponding return periods are calculated using the set of data provided from the seismic map of Barcis (Figure 6) and the interpolation formula (5).



(a) Skeleton curves for precast and cast-in-situ structures (b) Return periods from the seismic map of Barcis

Fig. 6 – Relations between PGA and IDR (a) and between PGA and return period (b)

The following step is to compute the probability of exceeding in 50 years for the obtained values of return periods by using equation (6). The lifespan of the structure is set to 50 years, as it is the service life for ordinary structures according to Eurocode. After having computed the cost damages of each limit state, the calculation of expected loss for each state is done and afterwards, the calculation of total expected loss. In Table 3, the calculation of total expected loss for both structures according the above procedure is given.

Table 3 – Total expected losses

Limit State	**Precast Structure**						**Cast-in-situ Structure**					
	IDR	PGA	T_R	R_{50}	Damage	Loss	IDR	PGA	T_R	R_{50}	Damage	Loss
	[%]	[g]	[years]	[%]	[€]	[€]	[%]	[g]	[years]	[%]	[€]	[€]
1	**0.75**	0.088	49.0	64.3	8'318	3'505	**0.50**	0.045	30.0	81.6	9'278	1'750
2	**1.50**	0.174	199.6	22.2	80'216	9'790	**1.00**	0.090	51.1	62.8	92'254	48'692
3	2.19	0.250	**475.0**	10.0	119'743	8'022	2.79	0.250	**475.0**	10.0	148'305	9'935
4	3.53	0.400	**1489.5**	3.3	988'163	32'631	5.15	0.400	**1489.5**	3.3	1'008'819	33'313
	Total expected loss (precast)					**53'947**	**Total expected loss (cast-in-situ)**					**93'690**

Therefore, the total cost of both buildings C_{TOT} is expressed as the sum of initial construction cost and the total expected loss as follows:

For precast structure: C_{TOT} = € 790'530 + € 53'947 = € 844'477

For cast-in-situ structure: C_{TOT} = € 807'055 + € 93'690 = € 900'745

3.4. Total Cost (Global Assessment Parameter)

3.4.1. Conversion of environmental impact into monetary unit

In order to compute the GAP for both structures, the first step is to convert the results of environmental impact into monetary unit.

Firstly, the environmental impact expressed in amount of greenhouse gas emissions needs to be converted in economic terms. According to the *European Emission Allowances - Global Environmental Exchange* [23], the price of 1 tonne of CO_2 during the first days of January 2016 was 8,05 *€/t*CO_2. Therefore, the environmental impact of the buildings during construction and demolition phases expressed in monetary terms is:

For *precast* structure: $R_{E(CO2)} = 198.3 \times € \ 8{,}05 = € \ 1'597$
For *cast-in-situ* structure: $R_{E(CO2)} = 232.9 \times € \ 8{,}05 = € \ 1'875$

Likewise, according Eurostat data [24], the electricity price for industrial sector in Italy for (year 2014) is 0,174 *€/kWh*. The cost of energy during the operation phase is: $R_{E(kWh)} = 2'055'300 \ kWh \times 0{,}174 \ €/kWh = € \ 357'622$.

According to *Eurostat* the price of natural gas in Italy for industrial sector is 0,035 $€/m^3$. Therefore, the cost of gas during 50 years of the operation phase is: $R_{E(gas)} = 913'027 \ m^3 \times 0{,}035 \ €/m^3 = € \ 31'956$. Hence, the total environmental impact in monetary unit is:

For *precast* structure: $R_E = R_{E(CO2)} + R_{E(kWh)} + R_{E(gas)} = € \ 391'175$
For *cast-in-situ* structure: $R_E = R_{E(CO2)} + R_{E(kWh)} + R_{E(gas)} = € \ 391'453$

3.4.2. Calculation of Global Assessment Parameter

The environmental and the structural costs are summed to evaluate the *GAP*. The numerical results are expressed in Table 4 and shown visually in Figure 7. From the results, it can be seen that the precast building is identified with the best performance in all categories.

Table 4 – Total expected losses

Cost [€]	Initial Cost	Environmental Impact	Total Exp. Loss	Glob. Asses. Parameter
Structure	I	R_E	L	R_{SSD}
Precast	790'530	391'175	53'947	1'235'652
Cast-in-situ	807'055	391'453	93'690	1'292'198

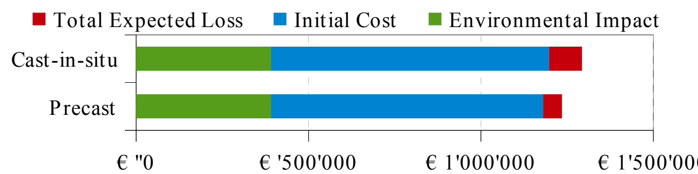


Fig. 7 – Total expected losses

4. Conclusions

The Sustainable Structural Design (SSD) method considers both structural and environmental parameters of the buildings in a life cycle perspective. It allows exchange of information among professionals of different fields to be obtained and involves different category stakeholders to make decisions between alternative solutions.

The comparison between different solutions is given in monetary unit. The most suitable solution is the one with the lowest value of Global Assessment Parameter, though it may have higher initial cost but requires less damage cost after an earthquake and/or has a better environmental performance.

The cost of greenhouse gas emissions results to be remarkably lower in comparison with the other costs due to the unreasonably low price of the CO_2 in the EU Emissions Trading System. In order to set the European economy on a path to decarbonization, the price of CO_2 should be increased to represent the real effects of global warming. The valuing process of CO_2 emissions involves many policymaking institutions and once the price would have its realistic value, the application of the methodology would be significantly improved.

The SSD method is a supporting tool for the general process of building design, with the aim to be a universal method that takes into account environmental and structural performance. It can be used to all type of constructions, from the existing ones that are subject of retrofitting, to new buildings during their design phase.

In a broader context, further improvements of the method can be obtained by taking into account not only seismic risk but different risk assessments, such as fire, wind, floods, etc.

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