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Energy and Buildings, Volume 110, 1 January 2016, Pages 149-158
http://dx.doi.org/10.1016/j.enbuild.2015.10.048
http://www.sciencedirect.com/science/article/pii/S0378778815303625

Post-Print Version

Does seismic risk affect the environmental impact of existing buildings?

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Abstract

The building sector significantly impacts on the environment during every stage of the building life cycle. The necessary transition toward a carbon-neutral society is driving a growing attention toward the refurbishment of old buildings, fostering intervention measures with the twofold objective of reducing operational energy consumption, typically upgrading the thermal insulation, and ensuring the quality of the consumed energy by adopting renewable and sustainable energy in the supply chain, such as thermal and photovoltaic solar energy.

In seismic prone areas the vulnerability of existing buildings, not designed according to modern building codes, could hamper the efficiency of the solely energy refurbishment, besides representing a safety hazard. The present paper investigates a framework to quantify the influence of seismic events on the environmental impact assessment of buildings.

The investigated framework is applied to a selected building, considering the building as alternatively located in regions with different seismicity. As an example, the building environmental impact is evaluated, in terms of carbon footprint, in the case of two different scenarios: upon completion of an energy refurbishment only, and after a coupled intervention targeting energy refurbishment and seismic

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retrofit. The results show that, in case of energy refurbishment only, the building located in a high-seismicity region presents an expected additional annual embodied equivalent carbon dioxide due to seismic risk, which almost equals the annual operational carbon dioxide after thermal refurbishment.

Keywords: Embodied carbon; Operational carbon; Sustainable refurbishment; Lateral load resisting systems; Seismic risk;

1. Introduction

It is nowadays widely acknowledged that the building sector significantly impacts on the environment during every stage of the building life cycle. Particularly, in the European Union (EU), the building sector [1] consumes up to 40% of the total EU energy and produces 36% of the total EU greenhouse gas emission. In addition, the reduction of operational energy consumption of existing buildings represents a priority of current over-national policies in Europe [2], particularly in establishing long term strategies for the national building stock refurbishment and high level of energy efficiency standards of the refurbished buildings [3, 4]. Considering the waste production, it is observed that the EU construction and demolition waste is about the 33% of the total amount of waste [1], indicating that demolition and re-construction, especially if extensively practiced, is not a sustainable strategy to enhance the performance of existing buildings.

In Europe, the existence of a wide portion of the existing building stock requiring restoration, in order to improve energy performance and building comfort, represents a challenge for environmental sustainability. A vast majority of the buildings requiring refurbishment were mainly built after the Second World War to rapidly meet the pressing housing demand during reconstruction. These buildings are typically multi-story houses with reinforced concrete (RC) frame structure, characterized by poor architectural features, built in the absence of urban planning and with high operational energy consumption, mainly due to the poorly insulated envelopes and obsolete plant equipment and finishing. The sustainable renovation of such buildings is typically addressed focusing on the reduction of the operational energy consumption and on the use of low-carbon materials in the refurbishment process, without accounting for the structural deficiencies, which could leave the building seriously unsafe and hamper the refurbishment investment, particularly in seismic prone areas; in fact the majority of these structures were built before the enforcement of modern seismic codes and before updated seismic classification of the European territory, and they are typically vulnerable with respect to seismic actions. Recent earthquakes in the Italian territory have emphasized this aspect, evidencing damage on many buildings, from residential constructions to monumental buildings [5] and industrial facilities [6], some of which previously undertook energy efficiency upgrades taking advantage of national subsidies. This situation highlights how, in the renovation process of existing buildings, in order to foster the transition toward an actually low-carbon society, the design-leading concept of eco-sustainability should be integrated by taking into account the assessment and mitigation of possible building structural vulnerabilities, especially in seismic prone territories.

Figure 1 shows a conceptual map depicting three possible scenarios of an existing building requiring energy renovation measures. In addition the building is considered vulnerable to seismic loads and having exhausted its structural service life; according to current building codes, the structural service life is typically 50 years for ordinary buildings.

The first scenario considers demolition and re-construction, given the extremely poor performance of the considered RC building stock. Upon completion of the intervention, the new building performance meets all up-to-date requirements on both energy consumption and structural safety; the new building end of life scenario includes selective dismantling and possible reuse or recycling of the construction materials. Noteworthy, however, if extensively practiced, demolition and re-construction may be not sustainable; indeed, the impact of such approach on the environment would be unbearably high both in terms of raw material consumption and hazardous-waste production. Furthermore, this approach would require relocation of the inhabitants.

The second scenario depicts common interventions targeting the sole energy refurbishment. This solution does not provide extension of the structural service life, and structural safety is not guaranteed in the case of an earthquake. Depending on the intensity of the seismic event either small or extensive repair measures, inhabitants' relocation and building's collapse could be experienced. It is worth noting that such a renovation practice does not include structural safety and preservation of human life among its priority targets. Ultimately, in the worst case scenario, no virtuous recycling and reuse can be foreseen in post-earthquake emergency management, but rather all debris of collapsed constructions may be disposed in landfills, increasing the environmental impact of the end-of-life phase.

The third scenario considers a more innovative approach, which couples energy-structural renovation. In particular, the structural renovation regards the introduction of new lateral force resisting systems embedded in the building new or improved envelope. This solution does not require inhabitants' relocation and meets safety requirements in the case of seismic loads. Noteworthy, the structural intervention allows lengthening the building structural service life, which would be left unchanged by any intervention aimed at upgrading the sole architectural and energetic performances; this integrated solution reduces the equivalent annual impact of the embodied energy given that the environmental load can be spread over a much longer time span.

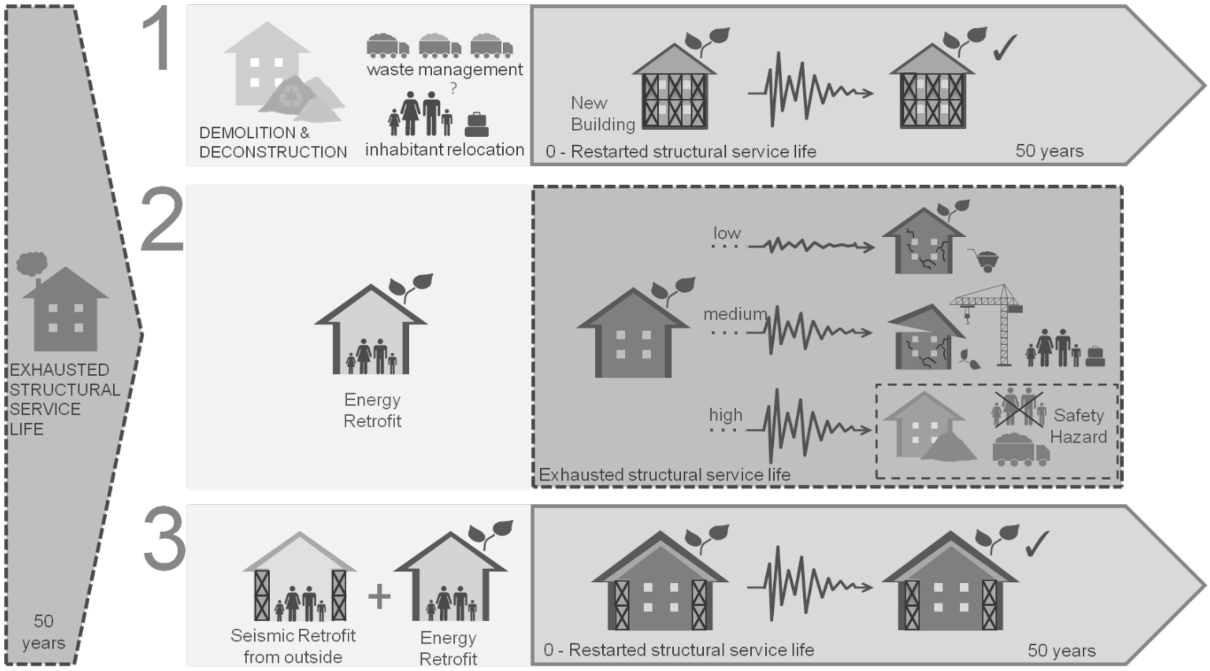


Figure 1 – Conceptual map of possible retrofit scenarios: 1) demolition and reconstruction; b) sole energy upgrade; 3) coupled energy and structural renovation.

The significance of accounting for seismic risk in the environmental assessment is also expressed in **Figure 2**, where the energy consumption, operational cost and carbon emission, among other variables, are expressed as a function of the building life (the time elapsed since its construction); the seismic impact is represented as an expected loss, expressed as annual energy consumption, being the seismic event uncertain in nature. **Figure 2(a)** considers a building energy retrofit intervention (R_E) targeting the nearly zero energy building performance. This intervention does not affect the building seismic behavior, therefore if a seismic event (X) occurs during the building life, there is an additional cost associated to the building post earthquake repair, which represents the actualization of the expected seismic loss. Interestingly the graph shows that, depending on the relevance of the annual energy consumption associated to the seismic risk, the nearly zero energy performance could be only theoretically attained, whereas actual consumption could be higher. Noteworthy, typical procedures adopted to evaluate the environmental impact of buildings [7-10] neglect this contribution, which could have even a greater impact when considering the problem at the district level. **Figure 2(b)** considers both building energy and seismic retrofit intervention ($R_{E,S}$). After the seismic retrofit the expected seismic loss is significantly reduced, therefore if a seismic event (X) occurs after the structural retrofit intervention, the additional cost due to the building repair is much lower than in the previous case. It is worth noting that, unlike sole energy refurbishment interventions, in the second case the structural retrofit allows the extension of the building structural service life as mentioned before.

This paper aims at ascertaining the influence and relevance of seismic risk on the environmental impact of existing buildings. A procedure to quantify the environmental impact induced by the seismic risk is presented, whose integration into a global LCA analysis is foreseen as a natural consequence, but is beyond the scope of this paper. Given a building and a site location, the main output of the investigated procedure is the expected annualized value of a selected environmental variable accounting for seismic risk. As a proof of concept, the investigated procedure is applied to a selected case study and the environmental impact associated to seismic risk is compared with the impact after thermal refurbishment, including or disregarding seismic retrofit. In the example, the embodied equivalent carbon dioxide (ECO_2e) is selected as the reference environmental variable for demonstration purposes and annual operational equivalent carbon dioxide (CO_2e) is adopted for comparative evaluations.

The preliminary results of the study reported herein indicate that the environmental impact associated to seismic risk could be relevant, showing potential for development and implementation of the procedure: for the selected building typology the expected annual ECO_2e due to seismic risk could be as high as the annual operational CO_2e after thermal refurbishment. This in turn entails that the results of traditional LCA analyses, expressed in terms of particular values of selected environmental variables, could be unrealistic: the additional contribution to such variables related to the seismic risk may be particularly relevant in the case of old buildings not designed according to modern building codes and located in regions with moderate to high seismicity; for such buildings, unless structural interventions are carried out, the envisioned target of nearly zero energy performance could be only theoretically attained, whereas actual consumption would be higher.

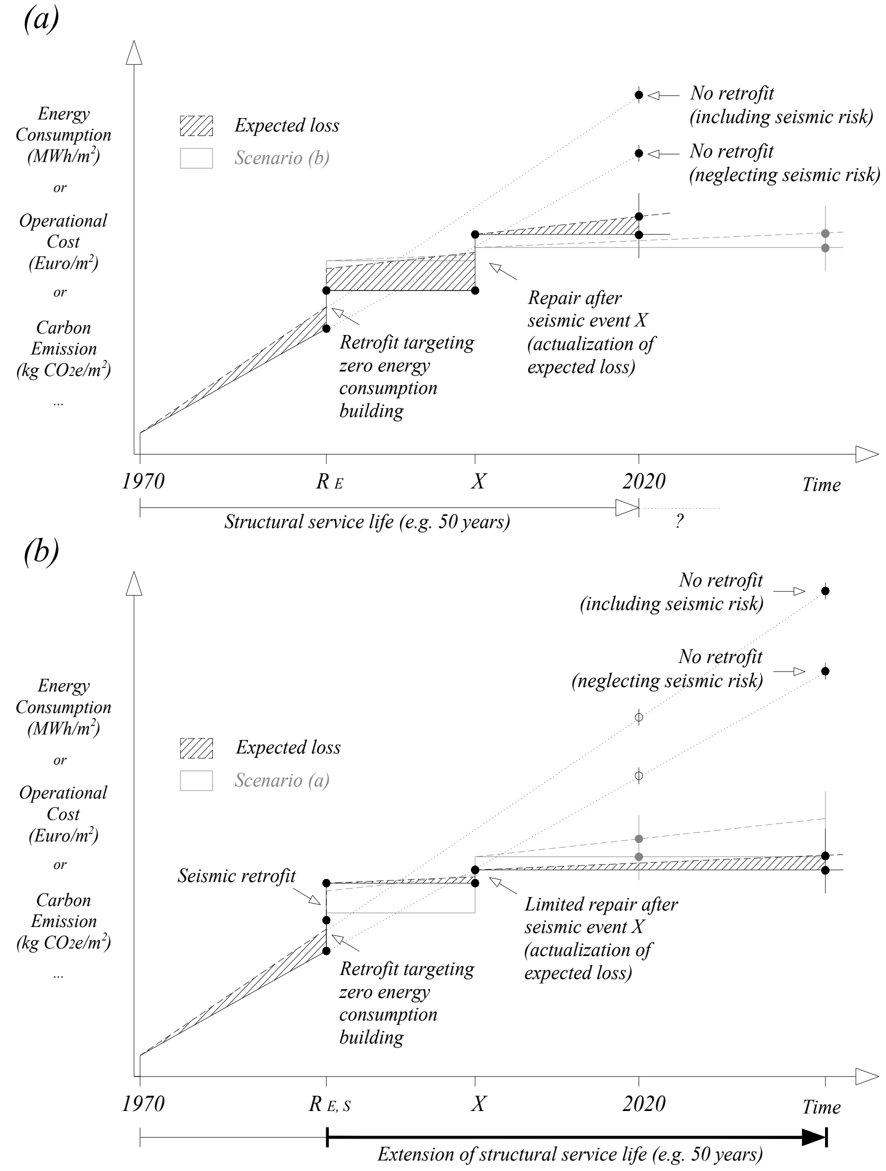


Figure 2 – Impact of energy consumption, operational cost and carbon emission during building life cycle. (a) energy retrofit intervention; (b) energy + seismic retrofit interventions

2. Sustainability assessment framework including seismic influence

It is widely acknowledged that the construction technique, the materials and the structural system influence all the environmental variables, such as the embodied and operational energy and carbon footprint of buildings, among others [11-15]. An attempt to specifically address the influence of the structural system in seismic prone areas has been recently made by some authors [16, 17]. Proietti et al. [16] included the structural characteristics of the adopted anti-seismic measures, particularly stiffening elements made of RC and steel, in the life cycle assessment of a passive house in Italy. Moussavi and Akbarnezhad [17] analysed a set of 15 lateral force resisting systems for a building designed for a moderate seismicity region including shear walls, moment resisting frames and braced frames finding significant differences in the life-cycle carbon.

A possible strategy to account for seismic risk is to take advantage of recently developed tools based on multi criteria decision making strategies such as MIVES (Model for Integration of Values for Evaluation of Sustainability) [18, 19]. MIVES is an integrated value model for sustainability assessment and allows the comparison of different types of indicators, such as environment, economic, aesthetic, functionality among others, by transforming each indicator into homogeneous values through value functions and by combining the obtained values through a weighting system, as for instance analytic hierarchy process. The MIVES output is a sustainability index useful to compare different entities, such as construction technologies or energy retrofitting solutions, under a multi objective perspective. Mosalam et al. [20] investigated the inclusion of structural performance and seismic loss analysis in the MIVES framework, while other researchers [21] directly summed the expected economic loss to converted monetary values of environmental variables, such as carbon emissions and energy consumption. In this paper, the seismic influence on the environmental impact assessment of buildings is evaluated directly in terms of expected values of selected environmental quantities, as it will be described in the following.

The investigated framework is derived from the probabilistic methodology developed at the Pacific Earthquake Engineering Research (PEER) centre; this methodology was specifically developed for performance based earthquake engineering (PBEE) and it is known as PEER-PBEE. The PEER-PBEE procedure [22] accounts directly for various sources of uncertainties; the output of the procedure is the prevision, in probabilistic terms, of the influence of possible seismic events on a given building at a given location, in terms of repair costs, downtime and casualties. Firstly, the conventional PEER-PBEE methodology is presented and, subsequently, the framework is extended to account for environmental variables.

2.1 Conventional earthquake engineering approach

The PEER-PBEE procedure is based on the total probability theorem and combines the probabilities related to four sets of uncertainties: seismic hazard, structural response, level of damage and monetary loss. The outcome of the procedure is the probability of exceedance (P) of a determined value of a decision variable (DV), typically human losses (deaths and serious injuries), direct economic losses (building repair or replacement cost), and indirect losses (repair time and unsafe placarding) resulting from building damage due to earthquakes. The probability of exceedance of a decision variable, given a building and a site location, provides the forecast probability that the decision variable will be exceeded in that particular building and site location during the building service life. For example, given an existing building in L'Aquila (Italy) with a structural service life of 50 years, the procedure could provide as output the probability that the repair cost following a seismic event is for instance 5% of the building replacement cost or the probability to record 7 serious injuries or the probability that 3 months will be required as repair time, among others.

To account for each set of uncertainties, the analysis is disaggregated into four phases (**Figure 3**).

In the hazard analysis, given a building and a site location, a hazard curve is determined considering the presence and type of faults, earthquake recurrence rates, site distance, soil conditions and so on. The hazard curve represents the annual frequency of exceedance of a certain value of a variable called intensity measure (IM); as for instance the annual frequency of exceedance of a certain peak ground acceleration, or the annual frequency of exceedance of a spectral ordinate corresponding to the structure fundamental period, among others.

The structural analysis regards the creation of a finite element model representing the structural system of the considered building. The analysis results are expressed in terms of engineering demand parameters (EDPs) conditioned to the seismic excitation $p[\mathrm{EDP}|\mathrm{IM}]$, where $p[\mathrm{X}|\mathrm{Y}]$ is the conditional probability of X given Y. EDPs are structural response quantities suitable to predict damage to structural and non-structural components and systems, such as inter-story drift ratio (ratio between story relative displacements and inter-story height), floor acceleration and floor velocity. Among EDPs, the best indicator of potential damageability for most structural systems and for many non-structural components is the inter-story drift ratio. Therefore $p[\mathrm{EDP}|\mathrm{IM}]$ could be seen as the probability that the inter-story drift at the first level (EDP) is for instance 2%, given a peak ground acceleration (IM) of 0.25 g.

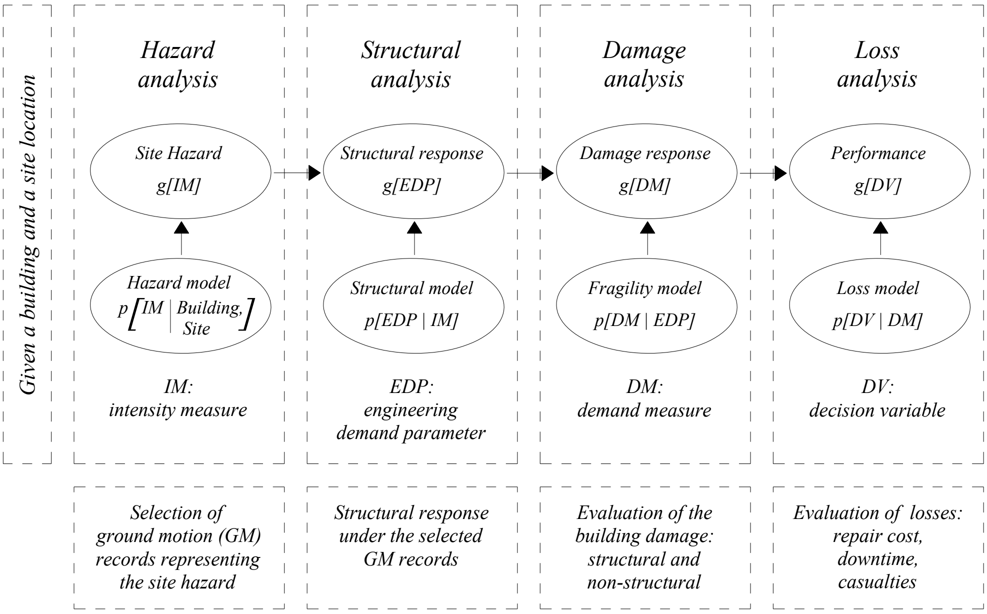


Figure 3 – PEER-PBEE Framework

Note: p[X|Y] *is the conditional probability of* X *given* Y*;* g[X] *is the occurrence frequency of* X

The damage analysis allows determining the damage level of one or more damageable groups related to the structural response. Damageable groups are for instance the columns of a given story, windows and masonry infills. Uncertainties of the structural response and of the capacity of structural and non-structural members are included in the analysis. The damage level is expressed by damage measures (DM) corresponding to the repair actions needed to restore each member to its original conditions. The damage analysis adopts fragility functions to determine the conditional probability of DM given EDP (*p*[DM|EDP]). Fragility functions are distributions that indicate the conditional probability of incurring a damage measure (DM) given a value of demand (EDP). For example the probability of incurring in reinforcement buckling (DM) of a RC column if the inter-story drift ratio (EDP) is for instance 2%. The fragility function is defined by a median demand value, μ, at which there is a 50% probability that DM will initiate, and a dispersion, β, which indicates uncertainty that DM will initiate at this value of demand.

The loss analysis determines the probability of exceedance of a decision variable (DV), such as the amount of economic losses, downtime or casualties, given a damage measure DM (*P*[DV|DM]). Uncertainties related to distribution of damage in the building and to fluctuation of market prices are included.

The results of each analysis are combined in a consistent manner according to the total probability theorem in terms of probability of exceedance of the decision variable (DV):

$$P\left[DV\right]=\iiint P\left[DV \mid DM\right] p\left[DM \mid EDP\right] p\left[EDP \mid IM\right] p\left[IM\right] \; dIM \; dEDP \, dDM \tag{1}$$

Where *P*[DV|DM] is the probability of exceedance of a determined value of the decision variable obtained from the loss analysis, *p*[DM|EDP] is the probability of a damage measure given an engineering demand parameter obtained from the damage analysis, *p*[EDP|IM] is the probability of an engineering demand parameter given an intensity measure obtained from the structural analysis and *p*[IM] is the probability of the intensity measure obtained from the hazard analysis.

For example, given an existing building in L'Aquila (Italy) with a structural service life of 50 years, *P*[DV] could be the probability that the repair cost after a seismic event (DV) exceeds for instance 5% of the building replacement cost; *P*[DV|DM] is the probability that the repair cost (DV) exceeds 5% of the building replacement cost if for instance reinforcement buckling (DM) of a RC column occurs; *p*[DM|EDP] is the probability of incurring in reinforcement buckling (DM) of a RC column if the inter-story drift ratio (EDP) reaches for instance 2%; *p*[EDP|IM] is the probability that the inter-story drift ratio (EDP) is 2% if the peak ground acceleration (IM) is for instance 0.25 g; finally p(IM) is the probability that the peak ground acceleration (IM) is for instance 0.25 g.

Considering a discrete number of variables and including the probability of collapse of the building, the previous multiple integral becomes a multiple summation:

$$P\left[DV\right]=\sum_{m}\left(\left(\begin{array}{l}\left(\sum_{j}\left(\sum_{i}\left(\sum_{k} P\left[DV_{j} \mid DM_{k}\right] p\left[DM_{k} \mid EDP_{j}^{i}\right]\right) p\left[EDP_{j}^{i} \mid IM_{m}\right]\right)\right) p\left[NC \mid IM_{m}\right]+ \\ +P\left[DV \mid C\right] p\left[C \mid IM_{m}\right]\end{array}\right) p\left[IM_{m}\right]\right) \tag{2}$$

Where p[NC|IM$_m$] is the probability of non collapse for the mth intensity measure, P[DV|C] is the probability of exceedance of a determined value of the decision variable if building collapse occurs and p[C|IM$_m$] is the probability of building collapse for the mth intensity measure. In the previous equation the subscripts m, j, i and k represent the counters of intensity measures, damageable groups, engineer demand parameters and damage measures respectively.

For practical implementation of the methodology, a software is freely available as a result of the ATC-58 project [23]. The software, referred to as the Performance Assessment Calculation Tool (PACT), performs the probabilistic computations and accumulation of losses. The reports contained in [23] describe how to obtain all the data necessary to run the electronic tool. In particular the software requires the hazard curve, released from national or international authorities, the results of the structural analysis and the selection of all the damageable elements, structural and non-structural, contained in the building. The software provides a collection of fragility curves and consequence actions for most common structural systems and building occupancies in USA. The output of the analyses relates to the consequences of seismic damage, including potential casualties, loss of use, and repair costs.

2.2 Investigated sustainability approach

The probabilistic framework presented in the previous paragraph is directly extendable to environmental variables [20] to evaluate sustainability:

$$P\left[SDV\right]=\int\int P\left[SDV\mid EM\right]p\left[EM\mid IM\right]p\left[IM\right]\ dIM\ dEM \tag{3}$$

Where P[SDV] is the probability of exceedance of a sustainability decision variable (SDV) adopted in the LCA analysis, as either global warming potential (GWP), expressed by equivalent carbon dioxide (carbon footprint), or photochemical ozone creation, ozone depletion potential, acidification and eutrophication potential, and resource depletion among others. P[SDV|EM] is the probability of exceedance of SDV given an energy measure (EM), as energy consumption in a building. p[EM|IM] is the probability of EM given an intensity measure (IM). p[IM] is the probability of an intensity measure.

For sustainability analysis the intensity measure is a climate variable such as the average outdoor temperature. For example, given an existing building in L'Aquila (Italy), P[SDV] could be the probability that the operational CO_2e exceeds for instance 10'000 kg per year; P[SDV|EM] is for example the probability that the operational CO_2e (SDV) exceeds 10'000 kg per year if the building operational energy (EM) is 30 kWh/m^2; p[EM|IM] is the probability that the building operational energy (EM) is 30 kWh/m^2 if the average outdoor temperature [IM] is for instance 15 °C; finally p[IM] is the probability that the average outdoor temperature is for instance 15 °C.

The same framework could be included in a multi-objective perspective [20], based on life cycle environmental cost analysis, or in a more general multi criteria decision making approach, such as MIVES [18, 19]. In the present paper the environmental variable is directly integrated into the conventional earthquake engineering approach, allowing the evaluation of the environmental impact of existing buildings due to seismic risk (here referred to as "PBEE-Green"). An environmental analysis is added to the "classical" loss analysis (**Figure 4**) in which the impact of each damage level is evaluated in terms of an environmental variable, such as the carbon footprint or embodied energy associated to structural or non-structural retrofitting following seismic damage, in addition to the output of conventional loss analysis as repair cost, repair time and casualties.

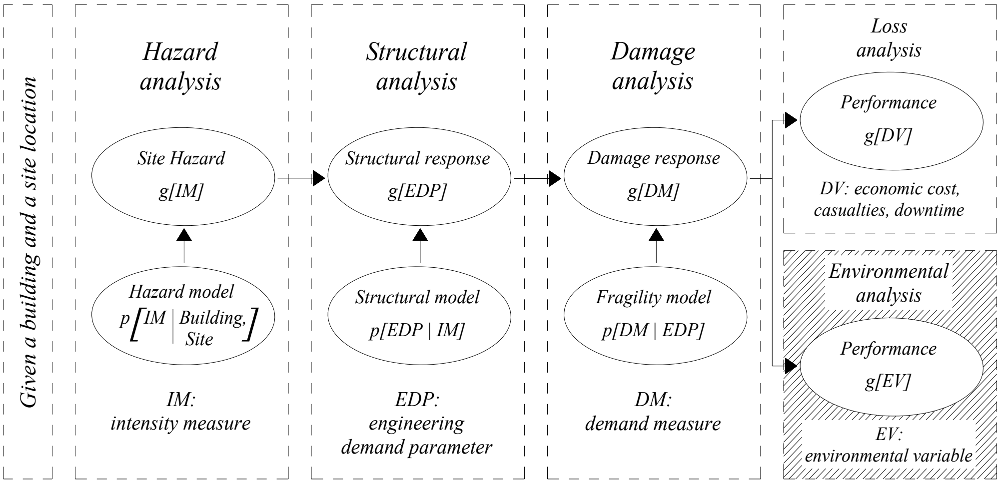


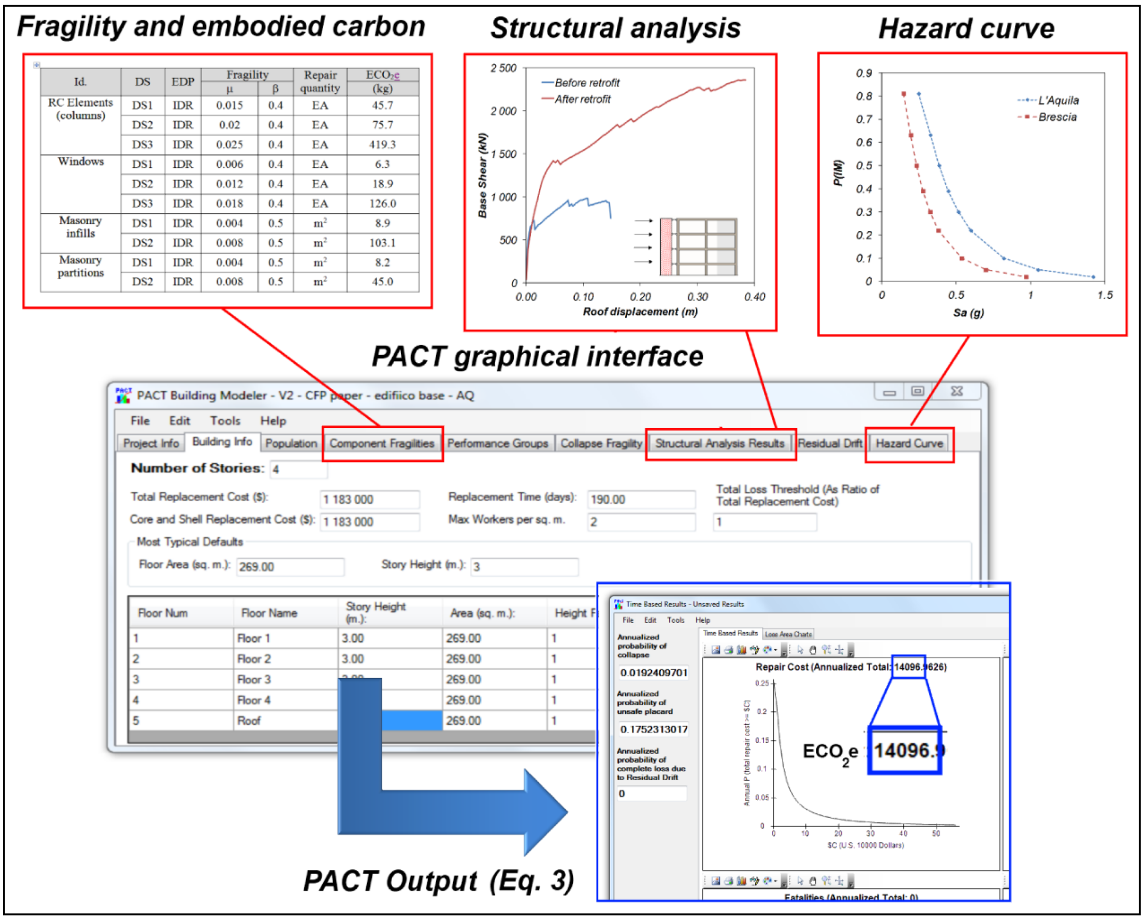
Figure 4 – PBEE-Green Framework

Considering a discrete number of variables and including the probability of collapse of the building the PBEE-Green entails the additional output:

$$P\left[EV\right]=\sum_{m}\left(\left(\begin{array}{l}\left(\sum_{j}\left(\sum_{i}\left(\sum_{k}P\left[EV_{j}\mid DM_{k}\right]p\left[DM_{k}\mid EDP_{j}^{i}\right]\right)p\left[EDP_{j}^{i}\mid IM_{m}\right]\right)\right)p\left[NC\mid IM_{m}\right]+\\ +P\left[EV\mid C\right]p\left[C\mid IM_{m}\right]\end{array}\right)p\left[IM_{m}\right]\right) \quad (4)$$

where *P*[EV|C] is the probability of exceedance of a determined value of the environmental variable if building collapse occurs.

For practical implementation of the methodology, it is still possible to use the PACT software developed for the PEER-PBEE framework [23]. To account for the influence of an environmental variable, it is necessary to substitute the building and repair costs, contained in the software libraries, with the values of the chosen environmental variable corresponding to each damage state, as for instance the ECO_2e emissions associated to a particular damage state and to the corresponding repair work. **Figure 5** shows a conceptual map of the procedure's implementation in the software PACT [23], with reference to the selected case study addressed in the next paragraph. The inputs of the software are the site seismicity, in terms of hazard curve, the building seismic vulnerability, as a result of the structural analysis, and the values of the chosen environmental variable associated to repair measures following seismic damage. The output of the procedure is the expected annual value of the chosen environmental variable, i.e. ECO_2e in the considered case study.



Id.	DS	EDP	Fragility		Repair quantity	ECO$_2$e
			μ	β		(kg)
RC Elements (columns)	DS1	IDR	0.015	0.4	EA	45.7
	DS2	IDR	0.02	0.4	EA	75.7
	DS3	IDR	0.025	0.4	EA	419.3
Windows	DS1	IDR	0.006	0.4	EA	6.3
	DS2	IDR	0.012	0.4	EA	18.9
	DS3	IDR	0.018	0.4	EA	126.0
Masonry infills	DS1	IDR	0.004	0.5	m^2	8.9
	DS2	IDR	0.008	0.5	m^2	103.1
Masonry partitions	DS1	IDR	0.004	0.5	m^2	8.2
	DS2	IDR	0.008	0.5	m^2	45.0

PACT Building Modeler - V2 - CFP paper - edifiico base - AQ

Number of Stories: 4

Total Replacement Cost ($): 1 183 000

Core and Shell Replacement Cost ($): 1 183 000

Replacement Time (days): 190.00

Max Workers per sq. m. 2

Total Loss Threshold (As Ratio of Total Replacement Cost) 1

Most Typical Defaults

Floor Area (sq. m.): 269.00

Story Height (m.): 3

Floor Num	Floor Name	Story Height (m.):	Area (sq. m.):	Height F
1	Floor 1	3.00	269.00	1
2	Floor 2	3.00	269.00	1
3	Floor 3	3.00	269.00	1
4	Floor 4		269.00	1
5	Roof		269.00	1

Time Based Results - Unsaved Results

Annualized probability of collapse: 0.0192409701

Annualized probability of unsafe placard: 0.1752313017

Annualized probability of complete loss due to Residual Drift: 0

Repair Cost (Annualized Total: 14096.9626)

Fatalities (Annualized Total: 0)

Figure 5 – Conceptual map of the procedure implementation in PACT [23]

3. PBEE-Green application example

The PBEE-Green procedure is applied to a selected case study in order to highlight its potentiality in integrating seismic risk in environmental analysis, particularly when substantial refurbishment interventions are envisioned to reduce building energy consumption in a seismic prone area. The considered case study is representative of Reinforced Concrete (RC) residential buildings constructed after the Second World War in the Italian territory, which represent about 50% of the Italian building stock [24]. These buildings, after a service life of more than 50 years, show structural and energy deficiencies: the former mainly due to design and construction before the enforcement of modern seismic codes, the latter due to poor thermal insulation performance of the envelope. Therefore a sustainable renewal is required under multiple perspectives: structural strengthening, energy efficiency upgrade and architectural renewal among others. A possible integrated retrofit solution accounting for all the cited requirements is represented by engineered double skin façades [25, 26].

Considering the demonstrative purpose of this application the following simplifications are applied:

(i) the chosen environmental variable is the carbon footprint associated to the embodied equivalent carbon dioxide emissions (ECO_2e) of the building and of the seismic retrofit interventions; only extraction of raw material, processing, production and disposal to landfills are considered; whereas other important impacts, such as those related to assembly of the components, manpower, and transport are disregarded. When all the phases of the retrofit interventions are reconsidered in a cradle-to-grave approach, the actual environmental impact associated to the seismic risk is expected to be higher. However, the simplified calculation presented herein serves as a proof of concept that seismic risk indeed impacts on the environment, whereas the exact computation of a LCA analysis lays beyond the scope of this paper and it is part of ongoing research. For the evaluation of the material embodied energy reference is made to the Inventory of Carbon and Energy (ICE v2.0) [27] of the University of Bath (UK), which collects statistical data from all major European databases and which is acknowledged as representative of the average impact of the European production;

(ii) the ECO_2e of the existing building is assumed as 1000 kg of ECO_2e per gross floor square area in m^2 [27-29];

(iii) the ECO_2e of the sole thermal refurbishment is estimated as 28 kg of ECO_2e per thermal panel insulation area in m^2, corresponding to polyurethane boards with 0.12m thickness, 126 kg of ECO_2e per window, corresponding to PVC framed windows, and 208 kg of ECO_2e per photovoltaic panel area in m^2 [27];

(iv) the ECO_2e of the building content and building dismantling are not considered herein;

(v) the ECO_2e of each element and of the repair measures are assumed lognormally distributed with dispersion $\beta = 0.4$.

The reference building (**Figure 6**) is considered located in Italy, with three floors and a basement (rectangular plan 27 m x 10 m). Based on the aforementioned assumptions, the total building ECO_2e, including thermal refurbishment, is 1’183’080 kg. The building is classified as energy efficiency class “D”, with an annual energy consumption of 90 kWh/m^2, corresponding to 72’630 kWh per year. After the thermal refurbishment the annual energy consumption is expected to be 30 kWh/m^2, equal to 24’210 kWh per year. The energy consumption before and after thermal refurbishment was evaluated through dynamic energy audits [26]. The associated operational carbon emissions are 48’444 kg of CO_2e and 16’148 kg of CO_2e before and after the thermal refurbishment. These values are based on the conversion factor 0.667 kg of CO_2e per kWh for the Italian energy production system [30].

Figure 6 – Considered building

Two location sites in the Italian territory are selected: Brescia (Northern Italy – moderate seismicity) and L’Aquila (Central Italy – high seismicity). **Figure 7** shows the hazard curve of each site, which represents the annual frequency of exceedance of the spectral ordinate corresponding to the structure fundamental period (T = 0.45 s). The spectral ordinate is representative of the building acceleration, and therefore inertia forces, during an earthquake.

The structural analysis phase allows evaluating the seismic performance of the considered building in the longitudinal and transverse directions (**Figure 8**), by means of nonlinear static analyses. The curves represent the structural response before and after a retrofit intervention consisting in the addition of external shear walls, 3 in the longitudinal direction and 4 in the transverse direction. The ECO_2e of the considered seismic retrofit is 39’900 kg (5’700 kg of ECO_2e per shear wall). The structural analysis allows determining the seismic demand associated to the building collapse, which is expressed in terms of earthquake return period. The return period is an estimate of the likelihood of an earthquake to occur: earthquake with low return periods will happen more often and will be typically characterized by lower intensity compared to earthquake with high return periods. The results of the analyses indicate that the return period associated to building's collapse are 495 and 182 years for the Brescia and L'Aquila location respectively, corresponding to a probability of exceedance of 9.6% and 24% during a building life of 50 years. After the seismic retrofit intervention, the return period for both locations is greater than 2475 years, corresponding to a probability of exceedance less than 2% in 50 years. It is worth noting that the collapse prevention limit state in the Italian territory for a new building with a service life of 50 years is associated to 975 years return period, corresponding to 5% probability of exceedance in 50 years.

The damageable elements (columns, windows, infills, among others) included in the damage analysis phase are listed in Table A.1 (Appendix A) in terms of damage state description and the consequent retrofit actions. The ECO_2e associated to the retrofit intervention, as part of the environmental analysis phase, is indicated in Table 1. The four phases of the PBEE-Green were automatically assembled by means of the Performance Assessment Calculation Tool (PACT) [23], according to the scheme presented in **Figure 5**.

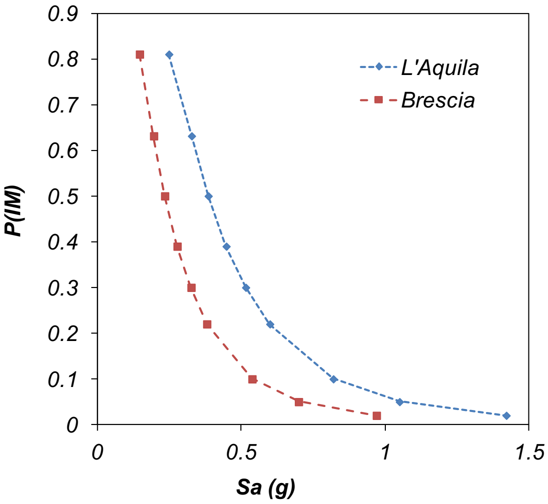


Figure 7 – Hazard curve for the considered building for two different sites: Brescia and L'Aquila (Italy).

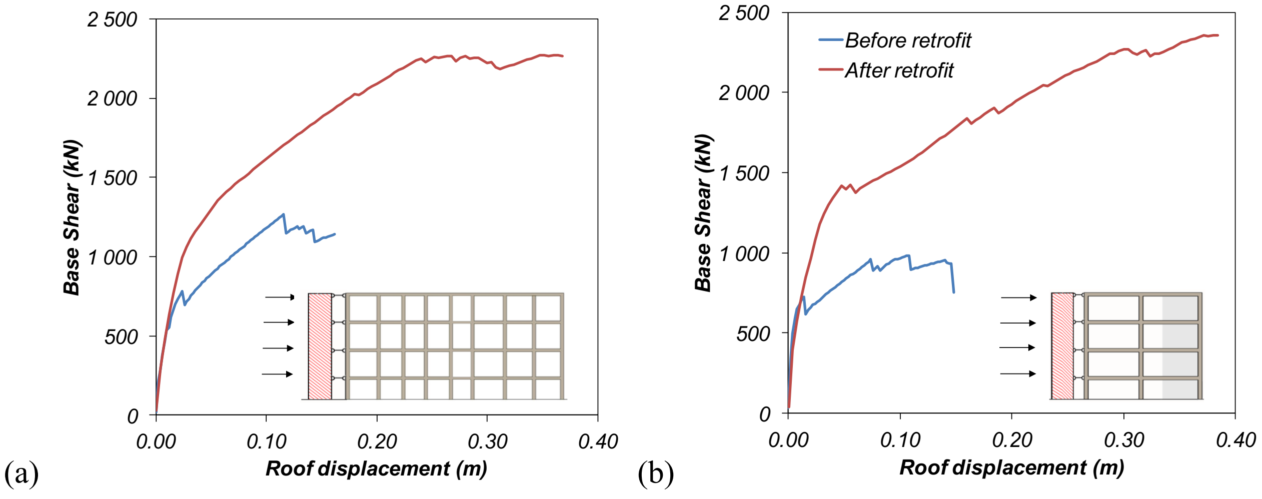


Figure 8 – Nonlinear static analysis results before and after retrofit:

(a) Longitudinal direction (b) Transverse direction

The main output of the PBEE-Green analysis is the expected annualized ECO_2e associated to the seismic restoration measures. These data can be compared to the operational CO_2e in order to evaluate the effectiveness in reducing carbon dioxide emission by the sole thermal refurbishment. In particular the expected annualized ECO_2e values for the building located in Brescia before and after the seismic retrofit are 3’986 kg and 438 kg respectively, while for the building located in L’Aquila the ECO_2e values are 14’096 kg and 1’602 kg respectively. It is worth remembering that the annual operational CO_2e before and after the thermal refurbishment is 48’444 kg and 16’148 kg respectively.

Therefore, the ratio between the expected annual embodied carbon dioxide associated to seismic risk and the annual operational carbon dioxide after the thermal refurbishment is 3% and 25% for the building located in Brescia, with and without structural retrofit respectively. 10% and 87% respectively for the building located in L’Aquila. Note that, following the simplified assumptions made in the analysis, the actual environmental impact associated to the seismic risk is underestimated, being limited to the sole embodied equivalent carbon dioxide of the materials.

Table 1 – Considered fragilities and embodied carbon dioxide of the retrofit intervention.

Note: DS = damage state (see Appendix A) 1 2 and 3 refer to increasing damage intensity; EDP = engineering demand parameter; IDR = inter-story drift ratio;

RA = roof acceleration (g); μ = median demand value; β = dispersion; EA = each element reported in column "Id."

Id.	DS	EDP	Fragility		Repair quantity	ECO_2e
			μ	β		(kg)
RC Elements (columns)	DS1	IDR	0.015	0.4	EA	45.7
	DS2	IDR	0.02	0.4	EA	75.7
	DS3	IDR	0.025	0.4	EA	419.3
Windows	DS1	IDR	0.006	0.4	EA	6.3
	DS2	IDR	0.012	0.4	EA	18.9
	DS3	IDR	0.018	0.4	EA	126.0
Masonry infills	DS1	IDR	0.004	0.5	m^2	8.9
	DS2	IDR	0.008	0.5	m^2	103.1
Masonry partitions	DS1	IDR	0.004	0.5	m^2	8.2
	DS2	IDR	0.008	0.5	m^2	45.0
Tile roofs	DS1	RA	1.4	0.3	m^2	2.3
	DS2	RA	1.7	0.3	m^2	27.7
Stairs	DS1	IDR	0.005	0.6	EA	135.0
	DS2	IDR	0.017	0.6	EA	1265.0
	DS3	IDR	0.028	0.45	EA	3900.0
RC wall (retrofit)	DS1	IDR	0.0084	0.5	EA	143.2
	DS2	IDR	0.012	0.45	EA	204.1
	DS3	IDR	0.019	0.5	EA	1392.7
Insulation panels	DS1	IDR	0.005	0.4	m^2	7.5
	DS2	IDR	0.012	0.5	m^2	14.7

Figure 9 shows the PBEE-Green results of the building after thermal refurbishment with and without seismic retrofit, in order to highlight the influence of site seismicity (**Figure 9a**) on the expected annual ECO_2e for the considered building. It is therefore evident that, for the selected building typology, the sole energy refurbishment does not guarantee environmental sustainability in seismic prone areas, particularly if seismic retrofit interventions are disregarded.

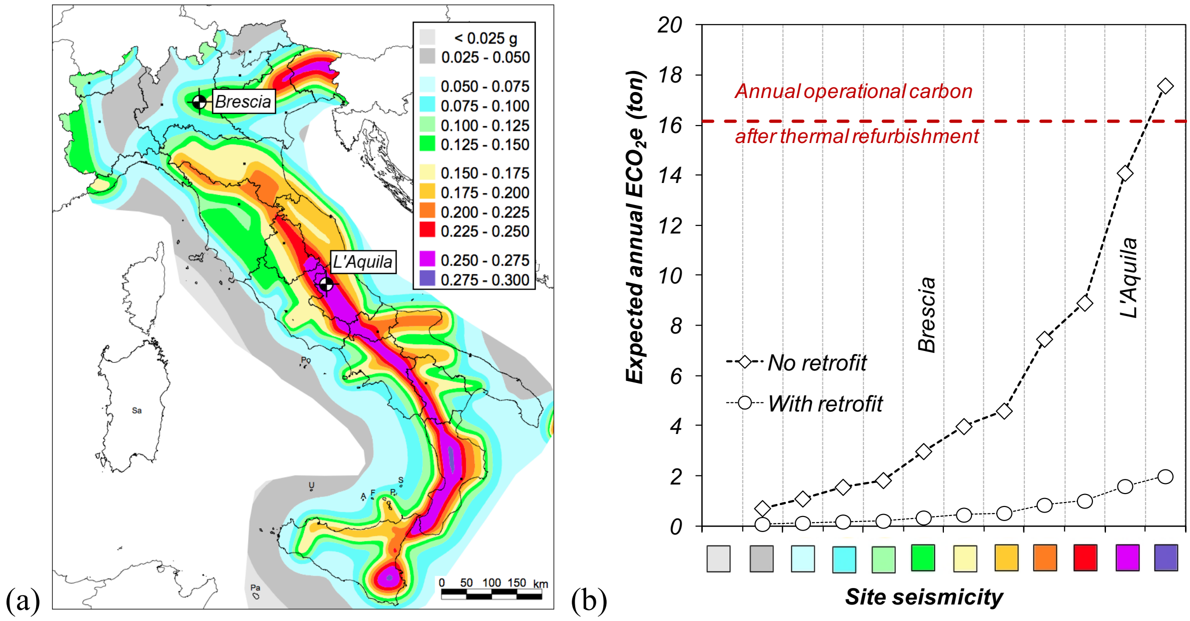


Figure 9 – (a) Seismic map of the Italian territory in terms of peak ground acceleration (in g) on stiff soil with a probability of exceedance of 10% in 50 years. (b) PBEE-Green results as function of site seismicity.

4. Conclusions

The structural vulnerability of existing buildings, resulting in major damage or even collapse during a seismic event, can substantially jeopardize the energy savings obtained with the solely energy retrofit interventions, beside representing a threat to the safety of people. Disregarding seismic risk may result in misleading expectations on the actual effect of extensive energy saving measures carried out at district or urban level. As a proof of concept, the PBEE-Green procedure was presented in the paper, which allows accounting for the environmental impact associated to the seismic risk in the global sustainability analyses, such as those carried out with life cycle assessment (LCA) and life cycle cost (LCC) procedures.

Starting from the probabilistic framework adopted in earthquake engineering, environmental variables can be directly associated to the seismic risk for buildings in earthquake prone areas. In the present paper the embodied equivalent carbon dioxide (ECO_2e) is taken as the reference variable; other variables could be selected such as embodied energy, photochemical ozone creation, ozone depletion potential, acidification and eutrophication potential among others. The main output of the PBEE-Green analysis is the expected annualized ECO_2e associated to seismic risk, thus associated to the retrofit measures following a seismic event. These data could be compared to the building operational carbon dioxide (CO_2e) or operational energy in order to evaluate the effectiveness in reducing greenhouse gas emission by the sole thermal refurbishment.

A case study was presented to highlight the potentiality of the investigated procedure. The reference building, which requires thermal insulation improvements to reduce building energy consumption, is supposed to be located in Italy in sites with either moderate or high seismicity and built before the enforcement of modern seismic building codes, therefore based on gravity load design and vulnerable to seismic actions. The ECO_2e associated to building erection, the CO_2e related to building operational energy and the ECO_2e associated to repair measures following a seismic event were accounted for. The environmental impact, in terms of carbon footprint, was evaluated in the case of two different scenarios: upon completion of an energy refurbishment only, and after a coupled intervention targeting energy refurbishment and seismic retrofit. The results of the PBEE-Green analysis show that the ratio between the expected annual ECO_2e associated to seismic risk and the annual operational CO_2e after the thermal refurbishment is 10% and 87% for the building located in a high seismicity region, with and without structural retrofit respectively.

The PBEE-Green procedure allowed evaluating the additional environmental cost in probabilistic terms associated to the seismic risk, thus emphasizing the substantial difference between the actual annual CO_2e that would be expected after either an intervention targeting the sole energy efficiency, or after a global intervention coupling energy efficiency and seismic risk mitigation measures. It was shown that such a difference significantly increases for increasing seismicity of the building site, being the annual expected ECO_2e associated to the seismic risk a large percentage of the CO_2e associated to the operational energy. This result further highlights the importance of multi-objective actions in earthquake prone areas.

Private and public authorities could adopt the PBEE-Green outcome, or encourage the adoption of the procedure, to account directly for seismic risk in the sustainability assessment of buildings, and in ascertaining the need and the effectiveness of conceived retrofit solutions. Increased confidence in the actual effect of special energy saving measures entails considerable investment guarantees, which may allow wiser allocation of public subsidies or encourage Energy Saving Companies in financing retrofit processes. This would in turn discourage consistent investment in energy efficiency measures for buildings having poor structural performance. Depending on the site seismicity, the target of nearly-zero-energy building, envisioned by International Standards as necessary to strive toward a carbon neutral society, can only be achieved if the adequate energy efficiency interventions are carried out on structurally safe constructions.

Acknowledgements

The assistance of Eng. Marco Santicoli in evaluating the embodied carbon of the various retrofit measures, and the contribution of Eng. Chiara Passoni in drafting Figure 1 is gratefully acknowledged.

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Appendix A

Table A.1 – Considered damageable elements; damage state descriptions and repair actions [27].

Id.	DS	Damage state description	Repair actions
RC Elements (columns)	DS1	Residual concrete crack widths exceed 1.5 mm. No significant spalling. No fracture or buckling of reinforcement.	Clean area adjacent to the damaged concrete. Prepare spalled concrete and cracks to be patched and to receive the epoxy injection. Patch concrete with grout. Replace and repair finishes.
	DS2	Columns exhibit residual crack widths > 1.5mm. Spalling of cover concrete exposes column transverse reinforcement but not longitudinal reinforcement. No fracture or buckling of reinforcement.	Shore damaged member(s). Remove damaged concrete beyond the exposed reinforcing steel. Place concrete forms. Place concrete. Remove forms. Remove shores after one week.
	DS3	Spalling of column cover concrete exposes a significant length of column longitudinal reinforcement. Crushing of column core concrete may occur. Fracture or buckling of reinforcement.	Shore damaged member(s). Remove damaged component. Place and splice (as necessary) new reinforcing steel to existing, undamaged reinforcing. Place concrete forms. Place concrete. Remove forms. Remove shores after one week.
Windows	DS1	Slight damage. Window suffers edge cracking, but not noticeable. Loss = 5% of replacement value.	Windows inspection, sealant substitution.
	DS2	Moderate damage. Window suffers edge cracking, some noticeable translation, some damage to glazing material. Loss = 15% of replacement value.	Remove and repair damaged components.
	DS3	Extensive damage. The window has cracked. For annealed monolithic and annealed laminated glass, the window remains in the pane without significant glass fallout. For fully tempered glass, the Extensive damage state immediately leads to essentially complete glass fallout. Loss = 100% of replacement value.	Remove damaged component and substitute with new window.
Masonry infills	DS1	Residual cracks in the panel exceed 1.5 mm.	Plaster removal, grout injections, plaster patches, painting.
	DS2	Extended crack pattern- corners of the infill crushed.	Removal and substitution of the damaged masonry panel.

Masonry partitions	DS1	Residual cracks in the panel exceed 1.5 mm.	Plaster removal, grout injections, plaster patches, painting.
	DS2	Extended crack pattern- corners of the infill crushed.	Removal and substitution of the damaged infill panel.
Tile roofs	DS1	Minor damage; tiles dislodged.	Replace and install dislodged tiles (assume 5% of area).
	DS2	Major portion of tile dislodged.	Replace and install dislodged tiles. (assume 60%).
Stairs	DS1	Non structural damage, local concrete cracking, localized concrete spalling, localized rebar yielding.	Patch, paint, epoxy injection.
	DS2	Structural damage but live load capacity remains intact. Extensive concrete cracking, concrete crushing, buckling of rebar	Remove damage components, install replacement components.
	DS3	Loss of live load capacity. Extensive concrete crushing, connection failure.	Replace stair.
RC wall (retrofit)	DS1	Spalling of cover, vertical cracks greater than 1/16 inch.	Epoxy inject cracks and patch spalled concrete.
	DS2	Exposed longitudinal reinforcing.	Shore wall, remove all concrete in damaged regions, replace concrete.
	DS3	Core concrete damage, buckled reinforcing, fractured reinforcing, shear failure, web failure, bond slip.	Replace wall or reinforce with R/C jacket if possible. Shore floor and wall, remove damaged concrete and steel, replace removed concrete and steel.
Insulation panels	DS1	Limited cracking at joints.	Repainting.
	DS2	Extended cracking at joints.	Plaster patch. Repainting.