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THE IMPACT OF EARTHQUAKES ON THE LIFE CYCLE CARBON FOOTPRINT OF EXISTING BUILDINGS.

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Abstract

The transition toward a low carbon society is nowadays recognized as a worldwide priority. In the building sector, such a mission is typically associated to the refurbishment of existing buildings by reducing the operational energy consumption and by moving toward sustainable and renewable energy in the supply chain. These actions are accomplished, among others, by the upgrade of the thermal insulation and the use of thermal and photovoltaic solar energy.

In earthquake prone regions, the refurbishment of existing buildings could be jeopardized by the damage associated to seismic events, especially if the considered buildings were not designed according to modern building standards. Therefore the application of solely energy-upgrade interventions on such buildings could lead to an unexpected and reduced environmental efficiency, besides representing a safety hazard.

In the present paper, the PEER-PBEE framework is specifically derived to address the embodied carbon of existing buildings related to seismic events. The investigated procedure is suitable for evaluating the effectiveness and environmental impact of the refurbishment of existing buildings in seismic prone areas. The procedure is applied to a selected case study after thermal refurbishment with and without seismic retrofit. The results, also projected at district level, show how inherent seismic vulnerability and site seismicity affect the environmental impact evaluation of the considered buildings.

Keywords: earthquake and sustainability; sustainable retrofit; sustainable refurbishment; carbon footprint.

1. Introduction

The need for refurbishment of existing buildings, aimed at improving the energy performance and the fruition of the building and its facilities, is an opportunity to promote the effective transition toward a low-carbon society. About 50% of the building stock in need of renovation was built after World War II, to quickly meet the pressing demand for housing during the post-war reconstruction. These buildings typically feature reinforced concrete frames designed to withstand gravity loads without accounting for seismic loads.

The sustainable refurbishment of such buildings is typically addressed through measures that reduce the operational energy consumption and by using sustainable materials for the requalification process, without accounting for the structural weaknesses that could jeopardize the efficiency of the investment in the case of extreme events, such as an earthquake. The considered buildings present intrinsic vulnerability to earthquakes since, most likely, they were built before the enforcement of modern anti-seismic building regulations and before a modern and comprehensive seismic classification of the European territory. This situation shows how the refurbishment of existing buildings should consider both the concept of eco-sustainability and the mitigation of possible structural vulnerabilities, particularly in high seismicity areas.

It has been widely recognized that the building typology, the structural system and the construction materials influence the environmental impact of buildings in terms of greenhouse gas emissions and embodied energy [1-4]. However, the influence of the seismic risk in the environmental impact assessment of refurbishment actions has not been investigated in depth. In Fig. 1 the carbon-footprint is expressed as a function of the life of the building, expressed as elapsed time since construction.

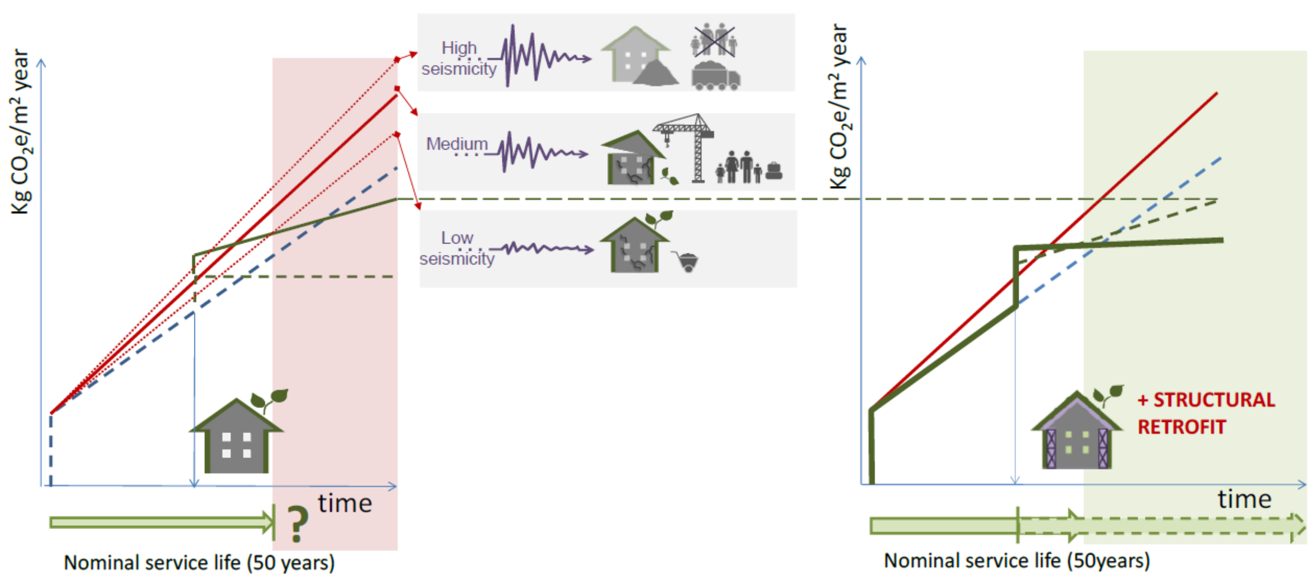

Fig. 1 – Influence of seismic vulnerability on environmental variables.

The predicted carbon-footprint is represented by the dotted blue line, showing the embodied equivalent carbon (CO_2e) accumulated during construction and the additional operational carbon. Following the energy refurbishment, aimed at reducing greenhouse gas emissions, the new equivalent carbon curve becomes the dashed green line. However, this energy saving is only virtual, because, as a result of possible earthquakes, additional equivalent carbon will be related to the repair measures and reconstruction after an earthquake. For the given structural vulnerability, the higher the seismic intensity, the higher the structural and non-structural damage and the higher the equivalent carbon associated to the retrofit. It is worth noting that the contribution of CO_2e associated to the seismic risk is an expected value, since the earthquake cannot be predicted in a deterministic way but only in statistical terms.

Following these considerations, the new equivalent carbon curve, including expected losses associated to the seismic risk, is the continuous green line. It is therefore evident the difference between the actual and predicted environmental impact [5]. This scenario highlights the need of new refurbishment strategies, targeting both the energy improvements needs and the structural retrofit as proposed in [6-8]. These approaches represent a more sustainable alternative to demolition and reconstruction of the building and they are characterized by interventions mainly from the outside, in order to limit the impact on residents.

2. Environmental sustainability considering seismic events

A possible way to consider seismic risk in the environmental impact assessment of refurbishment measures is the use of multi criteria decision making strategies such as MIVES (Model for Integration of Values for Evaluation of Sustainability) [9, 10]. MIVES is a model for the evaluation of sustainability that allows the comparison of different types of indicators, such as sustainability, economic, aesthetic and functionality, turning each indicator into homogeneous values through appropriate functions and by combining the obtained values through a weighting system.

Herein the environmental influence of the seismic risk is evaluated according to the PEER-PBEE framework [11]. This procedure (Fig. 2) starts from the various sources of uncertainties and provides as a result the prevision, in probabilistic terms, of the influence of possible seismic events on a given building at a given location, in terms of a decision variable (DV), such as repair costs, downtime and casualties. The analysis is subdivided into four steps: hazard analysis, structural analysis, damage analysis and loss analysis.

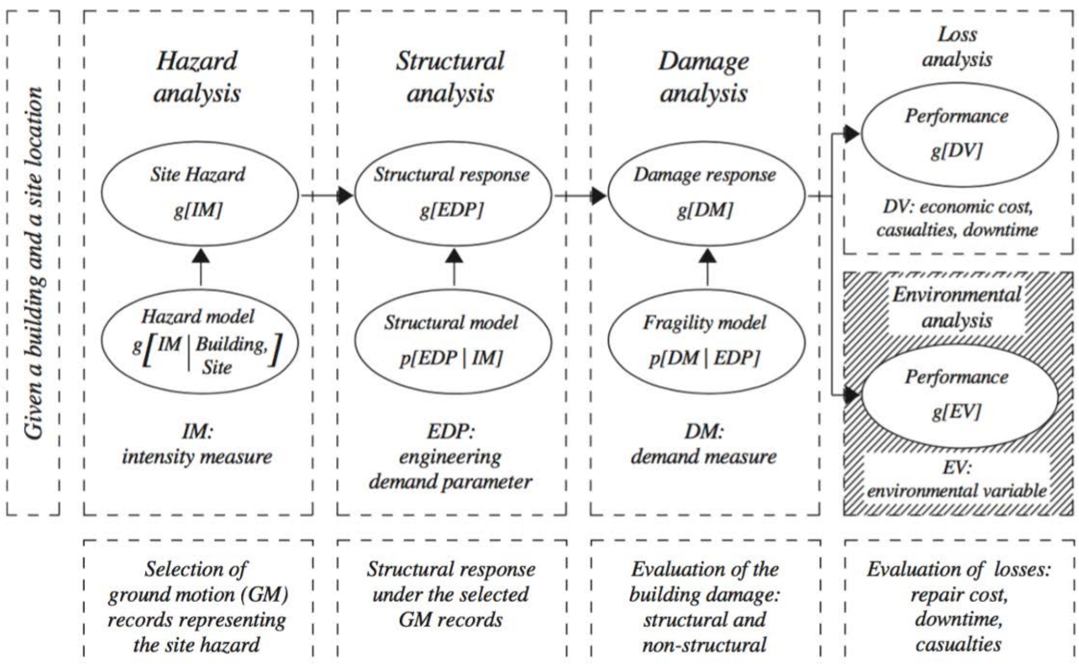

Fig. 2 – Considered probabilistic framework
Note: p[X|Y] is the conditional probability of X given Y; g[X] is the occurrence frequency of X.

In the *hazard analysis*, given a building and a site location, a hazard curve is defined taking into account the earthquake return period (corresponding to the rate of occurrence of earthquakes), the site distance from fault zones and local soil conditions. The hazard curve represents the annual frequency of exceeding a specific value of an indicator called intensity measure (IM). The *structural analysis* considers the creation of a numerical finite element model representing the structural system of the considered building. The results are expressed in terms of an engineering demand parameter (EDP) conditioned to the seismic excitation p[EDP|IM], where p[X|Y] is the conditional probability of X given Y. The *damage analysis* allows quantifying the loss of one or more elements groups in relation to the structural response. These elements groups are for instance the columns of a given floor, the windows and the masonry infills. The level of damage is expressed by damage measures (DM) corresponding to the repair actions needed to restore each member to its original condition. The *loss analysis* provides the probability of exceeding a decision variable (DV), such as economic losses, downtime or casualties, as a function of the damage measures DM (P[DV|DM]). The results of each analysis are combined with each other according to the total probability theorem in terms of probability of exceeding a decision variable (DV):

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

To account for the environmental impact of a seismic event [5], an additional analysis is added to the procedure described above (Fig. 2). In such analysis the impact of each damage level is assessed in terms of an environment variable such as the carbon-footprint or the embodied-energy associated to the structural or non-structural repair interventions.

3. Environmental sustainability at district level: case study

The procedure for the evaluation of the environmental impact connected to the seismic events is here applied with reference to a reference district located in seismic prone zones. This district is representative of the suburbs of the main European cities, where residential reinforced concrete (RC) buildings were built rapidly as a response of the global real estate boom occurred after World War II. Such building typologies, usually characterized by poor energy and seismic performances, represent about 50% of the European existing building stock [8]. Recently, a new holistic structural, architectural, and energy upgrading intervention targeting sustainability and resilience has been proposed for an integrated retrofit as mentioned before [6, 7].

The reference district is located in Brescia, a medium-seismicity Italian city. The district includes eight RC buildings with 4-to-6 stories and similar layouts (Fig. 3). The embodied equivalent carbon (CO_2e) of the district prior to energy efficiency upgrade is estimated as 59’650’000 kg, evaluated assuming 1000 kg of CO_2e per gross floor square area in m^2 [12]. Each building is classified in ‘energy class D’, with reference to the European energy classification for buildings, with an annual consumption equal to 90kWh/m^2 (3’060’000 kWh per year at district level). After the energy efficiency upgrade, the consumption drops to 30kWh/m^2 (1’020’000 kWh per year), corresponding to an ‘energy class A’. The CO_2 emissions associated to the operational use of the building prior and after the energy efficiency upgrade are 2’040’000kg and 680’000kg respectively, evaluated for the considered district. Such values are calculated adopting a conversion factor equal to 0.667kg of CO_2 per kWh related to the Italian energy production system.

Fig. 3 – Considered reference residential district.

The proposed procedure has been applied to the reference residential district by considering the potential damage caused by an earthquake to the structural elements of the buildings (columns, beams, and staircase walls) and to the non-structural elements (infill walls, partition walls, roof, and thermal insulation coating). The considered damage states [13] and the embodied equivalent carbon associated to seismic repair are reported in Table 1. It is worth noting that values presented herein underestimate the effective environmental impact at district level. The proposed values are associated to the single buildings, disregarding further impacts inherently associated to the infrastructures in "peace-time" (induced for example by low technical standards of the district electricity, gas, and water supply systems, aging of the pipes, lack of maintenance, possible water dispersions, etc.); furthermore, such values do not include the environmental impact associated to the repair of the infrastructures connected to the buildings, such as access roads, and district supply systems after an earthquake. A more refined estimation of the impact associated to the infrastructures is being investigated in an ongoing research work.

Table 1 – Considered damage states and CO_2e associated to seismic retrofit.

Element	Damage State	Description [13]	CO_2e (kg)
RC Elements (each)	DS1	Residual concrete crack widths exceed 1.5 mm. No significant spalling. No fracture or buckling of reinforcement.	45.7
	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.	75.7
	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.	419.3
Windows (each)	DS1	Slight damage. Window suffers edge cracking, but not noticeable.	6.3
	DS2	Moderate damage. Window suffers edge cracking, some noticeable translation, some damage to glazing material.	18.9
	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.	126.0
Masonry infills (m^2)	DS1	Residual cracks in the panel exceed 1.5 mm.	8.9
	DS2	Extended crack pattern- corners of the infill crushed.	103.1
Masonry partitions (m^2)	DS1	Residual cracks in the panel exceed 1.5 mm.	8.2
	DS2	Extended crack pattern- corners of the infill crushed.	45.0
Tile roofs (m^2)	DS1	Minor damage; tiles dislodged.	2.3
	DS2	Major portion of tile dislodged.	27.7
Stairs (each)	DS1	Non structural damage, local concrete cracking, localized concrete spalling, localized rebar yielding.	135.0
	DS2	Structural damage but live load capacity remains intact. Extensive concrete cracking, concrete crushing, buckling of rebar	1265.0
	DS3	Loss of live load capacity. Extensive concrete crushing, connection failure.	3900.0
RC wall – retrofit (each)	DS1	Spalling of cover, vertical cracks greater than 1/16 inch.	143.2
	DS2	Exposed longitudinal reinforcing.	204.1
	DS3	Core concrete damage, buckled reinforcing, fractured reinforcing, shear failure, web failure, bond slip.	1392.7
Insulation panels (m^2)	DS1	Limited cracking at joints.	7.5
	DS2	Extended cracking at joints.	14.7

Given these premises, as a comparison, extensive seismic retrofit interventions on all buildings composing the district have been considered in order to reduce both the collapse probability and the potential damage induced by an earthquake. This has been carried out by the introduction of external reinforced concrete walls connected to the building. Pushover analyses have been conducted. Being the considered buildings characterized by the same structural typology, the concept of seismic fragility of a building class could be adopted. The obtained results, in terms of inter-storey drifts and storey accelerations, have been included in the software Performance Assessment Calculation Tool (PACT) [13]. Such software is suitable to perform the probabilistic computations and accumulation of losses required under the PEER-PBEE framework [11]. To account for the influence of the embodied carbon associated to the retrofit following a seismic damage scenario, it is possible to substitute the repair costs contained in the available libraries with the embodied carbon corresponding to the repair at each damage state (Tab. 1, Figure 4).

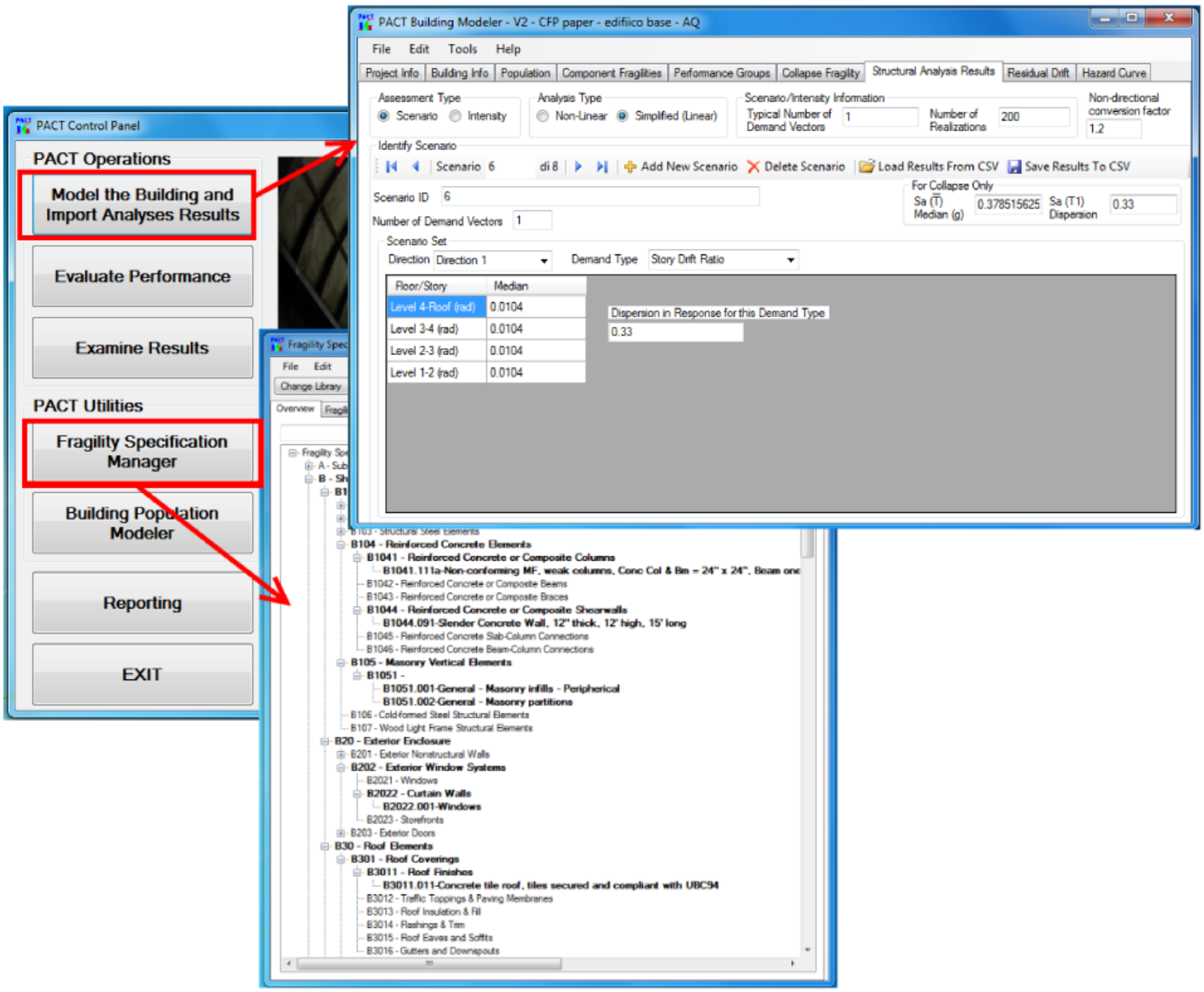

Fig. 4 – Screenshots of the software PACT [13]

The analysis results are expressed in terms of expected annual embodied CO_2e. This parameter is associated to the possible retrofit intervention needed after a seismic event for the given site seismicity. Such results may be compared to the operational CO_2 associated to the usage of the buildings in the district. The efficiency of sole energy upgrade interventions in the reduction of the global CO_2 emissions may thus be comparatively evaluated.

The results of this comparison are reported in Fig. 5 for the reference district, by assuming the district be located in different Italian zones characterized by different seismic hazard. It can be observed that the sole energy upgrade may not be considered as sustainable when seismic retrofit interventions are not contextually carried out, especially in higher seismicity areas. In particular, the ratio between the expected annual embodied CO_2e associated to seismic risk and the annual operational CO_2 after the thermal refurbishment is 3% and 25% for the building located in Brescia, considering or disregarding the structural retrofit. Such ratios increase up to 10% and 87% respectively in the case the district would have been located in higher seismic hazard zones, such as L'Aquila.

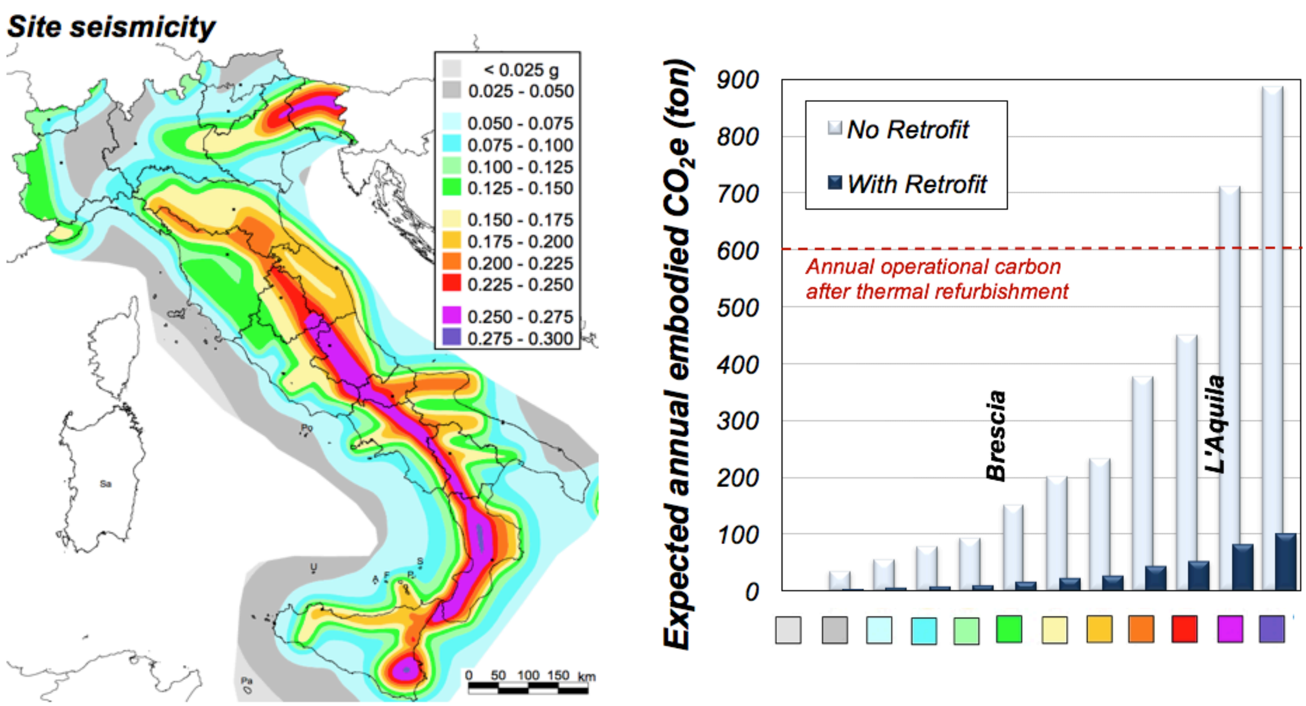

Fig. 5 – Environmental impact analysis results in terms of expected annual embodied CO_2e.

4. Conclusions

The seismic vulnerability of existing buildings may lead to high damage or even collapse of existing structures due to seismic events. This may jeopardize the efficiency of the sole energy upgrading measures in terms of reduction of the environmental impact, besides representing a threat for the human life. At district level, the expected reduction of the CO_2e emissions associated to operational usage of the building might be quite far from reality when the renovation strategies imply the sole energy renovation, disregarding the impact of possible seismic events or other natural hazard. For this reason, a procedure for the evaluation of possible losses connected to the seismic hazard in terms of environmental impact has been investigated. Such procedure may be implemented into global analyses aimed at assessing the environmental impact during the whole building life cycle, such as life cycle assessment (LCA) or life cycle cost (LCC) analyses.

Adopting the probabilistic approach typically implemented in performance engineering, the environmental variables may be directly associated to the seismic risk of structures located in seismic prone areas. Considering as environmental variable the equivalent embodied carbon associated to the seismic retrofit interventions required after earthquakes, the main analysis result is represented by the expected annual CO_2e associated to a particular building in a particular site. These data may be compared to the emissions connected to the building operational usage in order to assess the eco-efficiency of a sole energy upgrade-oriented retrofit intervention.

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