Critical Overview and Application of Integrated Approaches for Seismic Loss Estimation and Environmental Impact Assessment

M. Caruso, F. Bianchi, F. Cavalieri, and R. Pinho

Abstract Buildings are among the major contributors to environmental impacts, in terms of non-renewable resource depletion, energy and material consumption, and greenhouse gas (GHG) emissions. For this reason, modern societies are pushing towards the refurbishment of existing buildings aiming at the reduction of their operational energy consumption and at a major use of renewable energy and low-carbon materials. At the same time, buildings are expected to provide population with safe living and working conditions, even when hit by different kinds of hazards during their service life, such as earthquakes. Until recently, life cycle assessment (LCA) procedures tended not to include the effects of natural hazards. However, if considered in a building LCA, earthquake-induced environmental impacts would constitute a very informative performance metric to decision-makers, in addition to the more customarily used monetary losses or downtime indicators. Within this context, therefore, a comprehensive review of the existing literature is presented, with comparisons between available methodologies being carried out in terms of their employed seismic loss estimation method, environmental impact assessment procedure, damage-to-impact conversion, impact-to-cost conversion, and selected decision variable. Further, an illustrative case-study application is also included.

Keywords Seismic loss estimation · Environmental impact assessment · Sustainability · Life cycle assessment

---

M. Caruso (✉)
University School for Advanced Studies, IUSS Pavia, Pavia, Italy
e-mail: martina.caruso@iusspavia.it

F. Bianchi · F. Cavalieri
European Centre for Training and Research in Earthquake Engineering (EUCENTRE), Pavia, Italy

R. Pinho
Department of Civil Engineering and Architecture, University of Pavia, Pavia, Italy

E. B. Pereira et al. (eds.), *Proceedings of the 3rd RILEM Spring Convention and Conference (RSCC 2020)*, RILEM Bookseries 32,
https://doi.org/10.1007/978-3-030-76547-7_13

1 Introduction

Life cycle assessment (LCA) procedures are intended to estimate the environmental impacts of a process or a product, and they are often employed as a decision-making support instrument. For instance, buildings can be treated as large products with long and uncertain lives. Such procedures are characterised by four main steps, as described in [1] and [2]: (i) definition of goal and scope, (ii) life cycle inventory (LCI) analysis, including the assessment of energy and materials inflows and outflows associated to the building life cycle, (iii) life cycle impact assessment (LCIA), consisting in the quantification of impacts, and (iv) interpretation of the results, with these showing the major contributors, either materials or processes, to global environmental impacts in terms of specific performance metrics. Examples of metrics typically used in LCA procedures include global warming potential (GWP), non-renewable resource use, waste generation, and a wide range of human health impacts.

In the European Union (EU), the construction sector produces significant impacts on the environment, consuming up to 40% of the total EU energy and producing up to 36% of the total greenhouse gas (GHG) emissions [3]. For these reasons, there is a strong need of renovation mainly due to a progressive transition towards low-carbon and eco-efficient societies, as demonstrated by several national and European policies for building stock refurbishment. For instance, the European Green Deal, which is the new growth strategy for Europe, aims at a huge buildings' Renovation Wave, in order to achieve the ambitious energy and GHG reduction targets by 2030 and climate-neutrality by 2050 [4].

The ISO 21931:2010 [5] identifies three main stages in the building life cycle:

- **construction stage**, including raw materials extraction, transportation, component manufacturing and processing, as well as the construction process itself;
- **use stage**, including operational energy usage, building component maintenance, and resource inflow and waste outflow during the building operational phase;
- **end-of-life stage**, including building demolition, together with the transportation of waste or salvaged materials, processing and disposal of waste materials.

Notably, a recent European standard [6] introduced a beyond-life stage, including possible reuse, recycle and recovery of post-demolition materials.

Given that LCA involves the entire building life cycle, particular attention should be addressed to regions that are characterised by high risk of natural hazards, e.g. earthquakes, hurricanes, tornadoes, or floods, where hazardous conditions may result in additional environmental impacts. Until recently, LCA procedures have tended not to include such effects, however, earthquake-induced environmental impacts may constitute a meaningful metric to decision-makers, allowing easier comparisons between alternative design or retrofit strategies and providing tools to evaluate the potential benefits of retrofitting rather than demolishing and reconstructing. There is though still no unique opinion on how to include the additional environmental impacts due to natural hazards into an LCA.

The European building stock, being both earthquake-prone and heavily energy-consuming, needs a comprehensive strategy of renovation, due to its structural deficiencies and to its significant environmental impacts. The region is characterised by wide ranges of seismic areas and of climatic zones with high variability in seismic demands and energy needs for space heating and cooling. Nevertheless, the renovation rate is still very low due to high costs of intervention, downtime, potential need of inhabitants relocation and insufficient hazard-awareness. Furthermore, most of the retrofit interventions on existing building are solely intended to reduce either energy consumption or seismic vulnerability, neglecting potential correlations. However, in seismic prone sites, the vulnerability of buildings can compromise the efficiency and the monetary savings of a sole energy refurbishment. In addition, most of the buildings requiring refurbishment have almost exhausted their service life, being representative of a construction era with building codes lacking of seismic requirements.

Some studies ([7–9], among others) proved that the probability of damaging earthquakes during the building life cycle significantly influences the environmental impact assessment, and that post-earthquake repairs produce additional environmental impacts within a building LCA to be considered as additional construction stages. Earthquake damage can affect the remaining service life of a building and it can result in collapse or abandonment (i.e., end of service life), or in extensive repairs (i.e., extension of service life). Depending on when in the service life of the building the earthquake occurs, damage and repair may be meaningful in the overall LCA.

Furthermore, a minimal seismic retrofit in seismic prone regions may save materials and environmental initial costs, but may be ineffective against future earthquakes. On the contrary, a conservatively designed retrofit with higher initial costs may lead to a much better performance during earthquakes, thus reducing losses during the remaining service life of the building. Moreover, an integrated intervention in which the retrofit system may serve multiple purposes can represent an effective strategy for a better seismic and environmental performance. As an example, reinforced concrete shear walls may contribute not only to the structural upgrade but also to the thermal mass of the building and reduce the HVAC (Heating, Ventilation and Air Conditioning) demands and operational impacts. Also, an efficient choice of materials, for reduced energy demands, for durability, for future potential demolition and recycle, can significantly improve the environmental performance of a building. Thus, the most desirable scenario would be a coupled seismic and energy renovation. Unfortunately, integrated approaches have never been included into design codes due to the lack of a solid methodological framework.

2 Literature Review

Recent interest in sustainability of buildings has motivated a growing number of research endeavours focused on environmental impact assessment methods, and especially on the integration of those methods into seismic loss estimation frameworks. The differences between the results of the existing approaches is mainly related to the seismic loss estimation framework, the environmental impacts estimation method, the treatment of uncertainty and other aspects, as further discussed in this section.

A comprehensive review of the existing literature is presented herein, also by taking advantage of the similar efforts by Hasik et al. [10] and extending the comparison with a few other works. The aim of this review is to highlight potential strengths and limitations of the existing methodologies for a further understanding on how to properly combine the two aspects of seismic safety and environmental impact. The list of references is reported in Table 1 with information on (i) *authors and year of publication*, highlighting how the available literature on this topic is relatively scarce and recent, (ii) *seismic loss estimation method*, referring to the way the authors estimated the expected annual monetary losses due to potential earthquakes, (iii) *environmental impact assessment method*, indicating how building life cycle environmental impacts are quantified (iv) *damage-to-impact conversion method*, which is needed to assess the contribution to environmental impacts of each damage state defined within the seismic loss assessment, (v) *impact-to-cost conversion method*, which is used to translate the building's environmental impacts into monetary losses, and (vi) *decision variable*, i.e., the performance metric used.

2.1 Seismic Loss Estimation Method

Recent advances in the so-called performance-based earthquake engineering (PBEE) led to the development of the fully probabilistic PEER PBEE methodology [20], proposed by the Pacific Earthquake Engineering Research (PEER) Center, which is a probabilistic approach to estimate damage and the corresponding losses depending on the site-specific seismic hazard and on the structural response of a given building. Most studies included in this review referred to the well-known PEER PBEE framework for seismic loss estimation [21, 22], and used tools developed by the PEER Center to estimate earthquake-induced losses on buildings (e.g., the PACT Tool). The **PEER PBEE** procedure for seismic loss assessment has a four-step main structure: seismic hazard quantification at the site of interest, evaluation of structural performance under seismic hazard, estimation of damage in different building components conditioned on the estimated structural response, and calculation of losses due to repair the damaged components. The results of the procedure are in terms of mean annual frequency of exceedance of a certain value of a decision variable, such as monetary losses, downtime, casualties, or environmental impacts (carbon emissions or embodied energy).

While the PEER PBEE methodology is component-based, the software tool Hazus [23], developed by the Federal Emergency Management Agency (FEMA), is typically used to estimate post-earthquake losses at a local, state and regional scale. Some authors performed the seismic loss assessment using the Advanced Engineering

Table 1 Summary overview of past work on integrated approaches for seismic loss estimation and environmental impact assessment

Authors	Seismic loss estimation method	Env. impact assessment method	Damage-to-impact conversion	Impact-to-cost conversion	Decision variable
Menna et al. (2019) [11]	Other	–	–	Energy consumption	Monetary losses
Chhabra et al. (2018) [9]	Other	BOM LCA	–	Energy consumption and carbon footprint	Monetary losses
Lamperti Tornaghi et al. (2018) [12]	PEER PBEE	–	Damage/repair description + BOM LCA	–	Environmental impacts
Alirezaei et al. (2016) [13]	PEER PBEE	BOM LCA (Tally)	Repair-cost ratio	–	Environmental impacts
Belleri and Marini (2016) [8]	PEER PBEE	eCO_2 factors (references)	Damage/repair description + eCO_2 factors (ICE)	–	Environmental impacts
Calvi et al. (2016) [14]	Other	–	–	Energy consumption	Monetary losses
Padgett et al. (2016) [15]	Other	CO_2 factors (references)	–	Carbon footprint	Monetary losses
Wei et al. (2016) [16]	PEER PBEE	–	EIO LCA (EIO-LCA US 2002)	–	Environmental impacts
Arroyo et al. (2015) [17]	Hazus AEBM	eCO_2 factors (references)	Damage/repair description + eCO_2 factors (references)	–	Environmental impacts
Simonen et al. (2015) [18]	Other	BOM LCA (Athena IE)	Repair-cost ratio	–	Environmental impacts
Menna et al. (2013) [7]	Other	BOM LCA (IMPACT 2002+)	Damage/repair description + BOM LCA (IMPACT 2002+)	–	Environmental impacts
Comber et al. (2012) [19]	Hazus AEBM	EIO LCA (consultant)	EIO LCA (consultant)	–	Environmental impacts

Building Module (**Hazus AEBM**), added in the Hazus-MH Software to allow easier implementation of building-specific damage and loss functions by users.

Lastly, a few authors preferred custom approaches, referred to as **other**, mostly being similar either to PEER PBEE or Hazus. For instance, Menna et al. [11] and Lamperti Tornaghi et al. [12] used simplified versions of the PEER PBEE procedure, described in Vitiello et al. [24] and in Negro and Mola [25], respectively, while Calvi et al. [14] used the Displacement-Based Assessment [26].

2.2 Environmental Impact Assessment Method

Bill-of-materials (BOM), economic input-output (EIO), or hybrid procedures are alternative ways to assess environmental impacts, as described in [27]. In the works included in this review, environmental impacts were assessed with different LCA tools, performing either BOM or EIO LCA, or by applying eCO_2 factors.

BOM-based LCA (referred to as **BOM LCA**) requires individual materials quantities and processing needs and rely on available databases, such as U.S. LCI [28] or Ecoinvent [29]. Several proprietary LCA tools, like Athena Impact Estimator [30], Tally [31], SimaPro [32] or GaBi [33], among others, have been developed, based on ISO guidelines, and are available to perform BOM LCA of buildings.

On the contrary, EIO-based LCA (referred to as **EIO LCA**) requires only product or activity cost information to be used within available tools that translate industry sector-specific costs into the corresponding environmental impacts, such as the U.S. EIO-LCA [34]. This method can be used for a building LCA by either selecting a single sector best representing the building typology (e.g., construction of residential structures) or identifying multiple sectors (e.g., concrete manufacturing, or painting and coating), referred to as Building-EIO and Component-EIO, respectively.

As an alternative, environmental impacts can also be calculated via **eCO_2 factors** or estimates, available in literature or in databases, in which environmental impacts per kilograms of materials o per specific activities are collected. As an example, the Inventory of Carbon and Energy (ICE), developed at the University of Bath [35], collects carbon emissions per kilograms of material applicable to the European area. It is worth mentioning that the LCA boundaries of ICE data are from cradle to gate.

2.3 Damage-to-Impact Conversion Method

Environmental impacts can be treated in the same way as any other consequence function (e.g., economic losses) to be integrated within a seismic loss assessment. To do so, for each damage state (and consequent repair activity) defined in the seismic loss estimation framework for single components (or for an entire building), a damage-to-impact conversion is needed to get an estimate of their environmental impacts.

In the literature, as confirmed by Hasik et al. [10], damage and associated repair were converted into environmental impacts by one of the following three approaches:

- **EIO**: each repair activity is disaggregated into a list of processes to be assigned to specific industry sectors, whose costs are translated into environmental impacts via specific EIO tools, e.g., the U.S. EIO-LCA [34];
- **damage/repair description + BOM or eCO_2 factors**: impact data, resulting from a BOM LCA or via eCO_2 factors, are developed based on custom damage and repair descriptions and then introduced within the seismic loss assessment;
- **repair-cost ratio**: the economic losses due to repair are usually expressed as a percentage of the replacement cost of the building, and the same ratio can be applied to the building pre-use environmental impact to get the impacts of the repair activities.

2.4 Impact-to-Cost Conversion Method and Decision Variable

Some authors preferred to translate environmental impacts into costs so as to deal with a single decision variable, i.e., monetary losses due to both seismic risk and to building energy consumption or carbon footprint. This choice is specific of methods where earthquake-induced environmental impacts are neglected, and only the **energy consumption** of the building is considered from the environmental viewpoint. For instance, Calvi et al. [14] proposed the quantification of the energy annual cost as the ratio between cost of consumed energy and the total building replacement cost to allow a unique classification of seismic resilience and energy efficiency. A few other works translated the building **carbon footprint** into monetary losses by applying existing carbon tax rates.

However, Simonen et al. [36] demonstrated that embodied carbon and embodied energy are acceptable proxies for other environmental metrics, due to the perceived value to practitioners and potential users. For these reasons, in the works collected in this review, the selected decision variable was either in terms of **environmental impacts**, if a damage-to-impact conversion was adopted, or **monetary losses**, if the impact-to-cost conversion was used, neglecting energy-seismic correlations.

3 Application to a Case-Study (Using the FEMA P-58 Approach)

FEMA funded a series of projects, named ATC-86 and ATC-86-1 [37], to incorporate environmental impacts into the well-known FEMA P-58 seismic loss assessment methodology, currently implemented in the PACT Tool [21, 22, 27, 38], and thus to quantify earthquake-induced environmental impacts. This section discusses the application to a case-study of the FEMA P-58 approach.

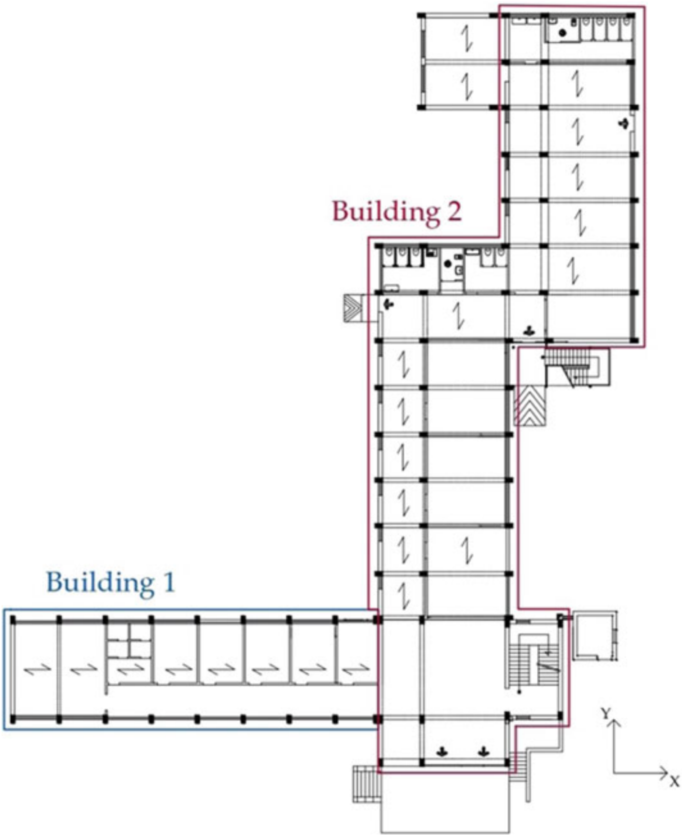

Fig. 1 Floor layout of the case-study

The case-study under scrutiny is one of the buildings of a school complex in Central Italy (i.e., Building 2 in Fig. 1). Although the original design documents are not available, comprehensive reports of in-site inspections and material tests suggest that the complex was built between the 60 s and the 70 s. It is a three-storey structure composed of sixteen reinforced concrete (RC) frames along the shortest direction X, with a U-shaped stair system, whose plan location produces an eccentricity in the building.

3.1 Numerical Modelling

Using the available information on the structural layout and the material properties [39], a refined 3D nonlinear numerical model of the case-study (Fig. 2) was developed with the fibre-based analysis software SeismoStruct [40].

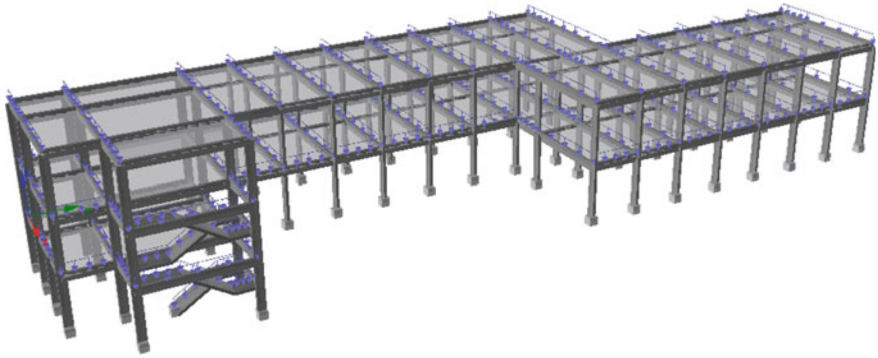

Fig. 2 Overview of the 3D nonlinear model on SeismoStruct [40]

Two materials were defined: existing concrete, with an average cylindrical compressive strength equal to 16.6 MPa and an elastic modulus approximately equal to 25,000 MPa, and existing steel for smooth reinforcement, with mean yielding strength equal to 391 MPa and an elastic modulus equal to 210,000 MPa. The material inelasticity was taken into account through Mander et al. [41] and Menegotto and Pinto [42] constitutive laws for concrete and steel, respectively. Force-based elements were used to model beams and columns, and elastic properties were assigned to the stairs system. Masonry external infills were not modelled explicitly, but only considered as applied loads on perimeter beams. Rigid diaphragms were deemed suitable to represent the rigid behaviour typical of concrete and hollow clay blocks mixed floors.

3.2 Application of Damage-to-Impact Conversion Methods

In the first version of the PACT tool, the results of loss assessments were only available in terms of dollars, deaths and downtime (i.e., the so-called 3Ds). However, in its latest version, environmental impacts, in terms of carbon emissions (CO_2) and embodied energy (EE), are included as consequence functions of damageable components, as suggested by Simonen et al. [36]. This section describes the application of the three damage-to-impact conversion methods introduced above, to estimate the earthquake-induced environmental impacts of the case-study via time-based assessments, based on simplified analysis (i.e., nonlinear static analysis).

Firstly, PACT requires the definition of a building performance model, i.e., a collection of data related to all the structural and non-structural components within the building that may experience damage during an earthquake. Thus, an inventory of drift-sensitive components was collected for the case-study. For RC structural components and masonry non-structural elements, the fragility and repair cost functions developed by Cardone [43] and Cardone and Perrone [44] were deemed appropriate for the case-study, since they are mostly suitable for pre-70 s RC frame buildings typical of the Italian existing building stock. In terms of environmental impacts, damage-to-impact conversion methods were needed to translate the damage states (DSs) defined for each component into the corresponding environmental impacts due to repair. As explained in Sect. 3.3, dedicated to damage-to-impact conversions, damage and associated repair activities were converted into environmental impacts by the following three approaches:

- **EIO LCA**: the environmental impacts per dollar spent within each specific sector were extrapolated from the web-tool EIO-LCA [31] for the industry sectors of interest and then summed up with their own weight (i.e., the percentage indicating the contribution of a single process to the global costs of the repair activity). The examples found in Simonen et al. [14] and FEMA [36] were taken as a reference to perform the calculations and to define the percentage distribution of cost allocations for the different components. For instance, for exterior masonry infills with windows, the following percentage distribution of costs was assumed for the DS at collapse: 4% adhesive, 10% clay product, 2% cleaning, 2% coating, 2% electrical, 3% glass, 10% piping, 5% plywood, 5% stucco, and 3% windows. The remaining cost percentage was allocated in labour, whose contribution to environmental impact is assumed equal to zero;
- **Repair description + eCO_2 factors**: as suggested by Belleri and Marini [6], the ICE database [32] was used to get the eCO_2 emissions per kg of material (e.g., concrete, glass, clay). Average embodied carbon estimates equal to 0.11, 1.44, 0.24 kg eCO_2 per kg of concrete, glass and clay bricks, respectively, were selected. The main issue related to this approach is the need to estimate the kilograms of material that needs to be replaced during the repair activity associated to specific DSs. A unit volume of material was assumed for the DS at collapse (i.e., in case of full replacement of the component), while partial volumes of material associated to intermediate DSs were scaled down proportionally to DS-specific repair costs to finally assign the eCO_2 at each DS;
- **Repair cost-ratio**: given that the expected annual loss (EAL) ratio is the ratio between the expected value of the loss exceedance curve and the building's replacement value, the environmental impacts due to repair activities were calculated by multiplying the EAL ratio in terms of monetary losses and the replacement value in terms of environmental impacts (estimated through a Building-EIO and equal to approximately 650,000 kg eCO_2). A significant assumption of this approach is related to the fact that also labour costs are included, so the cost percentage allocated to labour should be excluded from the comparison. However, since the estimation of earthquake-induced monetary losses is needed, this procedure was performed after running the loss analysis on PACT and the impacts deriving from this approach are presented in Sect. 3.3.

In conclusion, the environmental impact consequence functions, whose medians in terms of eCO_2 were calculated following the first two approaches above, were assumed lognormally distributed, with dispersion equal to 0.4.

Table 2 eCO_2 resulting from different damage-to-impact (DTI) conversion methods

DTI	eCO_2 (kg eCO_2/yr)	eCO_2 (% ReI)
EIO LCA	1,600	0.24
Description + ICE	1,800	0.28
Repair-cost ratio	2,000	0.30

3.3 Discussion of the Results

The results of time-based performance assessments are mainly expressed in terms of loss curves, which plot the total expected loss as a function of the annual probability of exceedance of that loss. From PACT loss analysis results, an EAL ratio equal to 0.4% was estimated as the ratio between the area underneath the monetary loss curve (approximately equal to € 5,000) and the total replacement cost (approximately equal to € 1.25 million). Concerning environmental impacts, the expected annual carbon emissions obtained by applying the three different damage-to-impact conversion methods described above are shown in Table 2, also expressed as a percentage of the building's replacement impact (ReI). As stated above, labour does not contribute to environmental impacts and its contribution was assumed equal to the 20% of global repair costs. Thus, the impacts due to post-earthquake repairs arising from the repair-cost ratio approach were recalculated as the 80% of the eCO_2 resulting from the approach (i.e., equal to 2.5 t eCO_2). It is worth remembering that the cost percentage assigned to labour may vary significantly depending on the activity of interest.

4 Conclusions

A review of the available literature on integrated approaches for seismic loss estimation and environmental impact assessment was presented, together with the application to a case-study of the FEMA P-58 approach. The critical review of the existing approaches showed that earthquake-related losses and impact may be significant in an overall LCA, thus research is needed to further develop and validate a methodological framework to assess such impact. The application of the FEMA P-58 demonstrated that it can be used to quantify earthquake-induced environmental impact (as done already for monetary losses).

Notably, the three damage-to-impact conversion methods described above lead to very similar estimates of carbon emissions, demonstrating an already relatively satisfactory robustness of the three different approaches despite their very diverse assumptions and required information. It is worth emphasising the lack of comprehensive inventories from where to collect information on environmental impacts of specific components or activities. Furthermore, often the available databases are not updated to the current market prices, thus adjustment factors are needed to adapt the estimates to the present material or activity prices specific for the site of interest, increasing the uncertainty of the results.

Acknowledgements This work has been carried out within the framework of the WP5 activities (focused on the development and verification of integrated seismic and energy retrofitting solutions) of the ReLUIS-DPC 2019–2021 research project, funded by the Italian Civil Protection Department.

References

1. ISO 14040:2006: Environmental management—Life Cycle Assessment—Principles and framework. International Organization for Standardization (ISO). Geneva (2006)
2. ISO 14044:2006: Environmental management—Life Cycle Assessment—Requirements and guidelines. International Organization for Standardization (ISO). Geneva (2006)
3. European Commission: Energy-efficient Buildings PPP beyond 2013: Research & Innovation Roadmap. Brussels (2012)
4. European Commission: The European Green Deal. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee of the Regions - COM(2019) 640 final. Brussels (2019)
5. ISO 21931:2010: Sustainability in building construction—Framework for methods of assessment of the environmental performance of construction works—Part 1: Buildings. International Organization for Standardization (ISO). Geneva (2010)
6. EN 15978:2011: Sustainability of construction works—Assessment of environmental performance of buildings—Calculation method. European Committee for Standardization (CEN). Brussels (2011)
7. Menna, C., Asprone, D., Jalayer, F., Prota, A., Manfredi, G.: Assessment of ecological sustainability of a building subjected to potential seismic events during its lifetime. Int. J. Life Cycle Assess. **18**(2), 504–515 (2013)
8. Belleri, A., Marini, A.: Does seismic risk affect the environmental impact of existing buildings? Energy Build. **110**, 149–158 (2016)
9. Chhabra, J.P., Hasik, V., Bilec, M.M., Warn, G.P.: Probabilistic assessment of the life-cycle environmental performance and functional life of buildings due to seismic events. J. Arch. Eng. **24**(1), 04017035 (2018)
10. Hasik, V., Chhabra, J.P., Warn, G.P., Bilec, M.M.: Review of approaches for integrating loss estimation and life cycle assessment to assess impacts of seismic building damage and repair. Eng. Struct. **175**, 123–137 (2018)
11. Menna, C., Vitiello, U., Mauro, G., Asprone, D., Bianco, N., Prota, A.: Integration of seismic risk into energy retrofit optimization procedures: a possible approach based on life cycle evaluation. In: IOP Conference Series: Earth and Environmental Science 290, 012022. IOP Publishing (2019)
12. Lamperti Tornaghi, M., Loli, A., Negro, P.: Balanced evaluation of structural and environmental performances in building design. Buildings **8**(4), 52 (2018)
13. Alirezaei, M., Noori, M., Tatari, O., Mackie, K.R., Elgamal, A.: BIM-based damage estimation of buildings under earthquake loading condition. Procedia Eng. **145**, 1051–1058 (2016)
14. Calvi, G.M., Sousa, L., Ruggeri, C.: Energy efficiency and seismic resilience: A common approach. In: Multi-hazard Approaches to Civil Infrastructure Engineering, pp. 165–208. Springer (2016)
15. Padgett, J.E., Li, Y.: Risk-based assessment of sustainability and hazard resistance of structural design. J. Perform. Construct. Facilities **30**(2), 04014208 (2016)
16. Wei, H.-H., Skibniewski, M.J., Shohet, I.M., Yao, X.: Lifecycle environmental performance of natural-hazard mitigation for buildings. J. Perform. Construct. Facilities **30**(3), 04015042 (2016)

17. Arroyo, D., Ordaz, M., Teran-Gilmore, A.: Seismic loss estimation and environmental issues. Earthquake Spectra **31**(3), 1285–1308 (2015)
18. Simonen, K., Merrifield, S., Almufti, I., Strobel, K., Tipler, J.: Integrating environmental impacts as another measure of earthquake performance for tall buildings in high seismic zones. Struct. Congress **2015**, 933–944 (2015)
19. Comber, M.V., Poland, C., Sinclair, M.: Environmental impact seismic assessment: application of performance-based earthquake engineering methodologies to optimize environmental performance. Struct. Congress **2012**, 910–921 (2012)
20. Porter, K.A., Beck, J.L., Shaikhutdinov, R.V.: Investigation of sensitivity of building loss estimates to major uncertain variables for the Van Nuys testbed. Pacific Earthq. Eng. Res. Center, Berkeley (2002)
21. FEMA: Seismic Performance Assessment of Buildings Volume 1-Methodology. Rep. No. FEMA P-58-1 (2018)
22. FEMA: Seismic Performance Assessment of Buildings Volume 2-Implementation Guide. Rep. No. FEMA P-58-2 (2018)
23. Kircher, C.A., Whitman, R.V., Holmes, W.T.: HAZUS earthquake loss estimation methods. Nat. Hazards Rev. **7**(2), 45–59 (2006)
24. Vitiello, U., Asprone, D., Di Ludovico, M., Prota, A.: Life-cycle cost optimization of the seismic retrofit of existing RC structures. Bull. Earthq. Eng. **15**(5), 2245–2271 (2017)
25. Negro, P., Mola, E.: A performance based approach for the seismic assessment and rehabilitation of existing RC buildings. Bull. Earthq. Eng. **15**(8), 3349–3364 (2017)
26. Welch, D., Sullivan, T., Calvi, G.: Developing direct displacement-based procedures for simplified loss assessment in performance-based earthquake engineering. J. Earthq. Eng. **18**(2), 290–322 (2014)
27. FEMA: Seismic Performance Assessment of Buildings Volume 4- Methodology for Assessing Environmental Impacts. Rep. No. FEMA P-58-4 (2018)
28. National Renewable Energy Laboratory: U.S. LCI, https://www.nrel.gov/lci/ (2012)
29. Swiss Centre for Life Cycle Inventories: Ecoinvent v3.6. https://www.ecoinvent.org/
30. Athena Sustainable Materials Institute: Impact estimator for buildings. http://www.athenasmi.org/
31. KT Innovations: Tally. https://choosetally.com/
32. PRé Consultants: SimaPro 9.0. https://simapro.com/
33. Thinkstep: GaBi v2.0. http://www.gabi-software.com/
34. Weber, C., Matthews, D., Venkatesh, A., Costello, C., Matthews, H.: The 2002 US benchmark version of the economic input-output life cycle assessment (EIO-LCA) model. Green Design Institute, Carnegie Mellon University. http://www.eiolca.net/ (2009)
35. Hammond, G.P., Jones, C.I.: Embodied energy and carbon in construction materials. Proc. Inst. Civil Eng. Energy **161**(2), 87–98 (2008)
36. Simonen, K., Huang, M., Aicher, C., Morris, P.: Embodied carbon as a proxy for the environmental impact of earthquake damage repair. Energy Build. **164**, 131–139 (2018)
37. Court, A., Simonen, K., Webster, M., Trusty, W., Morris, P.: Linking next-generation performance-based seismic design criteria to environmental performance (ATC-86 and ATC-58). Struct. Congress **2012**, 922–928 (2012)
38. FEMA: Seismic Performance Assessment of Buildings Volume 3- Supporting Electronic Materials. Rep. No. FEMA P-58-3 (2018)
39. Prota, A., Di Ludovico, M., Del Vecchio, C., Menna, C., Frascadore, R., Palladino, F., Di Sarno, L.: Caso studio: Scuola "G. Parozzani"—Scheda di sintesi interventi. Progetto DPC_ReLUIS 2019–2021 (WP5)
40. Seismosoft: SeismoStruct—A computer program for static and dynamic nonlinear analysis of framed structures, http://www.seismosoft.com (2020)
41. Mander, J.B., Priestley, M.J., Park, R.: Theoretical stress-strain model for confined concrete. J. Struct. Eng. **114**(8), 1804–1826 (1998)

42. Menegotto, M., Pinto, P. E.: Method of analysis for cyclic loaded R. C. plane frame including changes in geometry and non-elastic behaviour of elements under combined normal force and bending. In: Proceedings of IABSE Symposium on Resistance and Ultimate Deform ability of Structures Acted On by Well Defined Repeated Loads 11, pp. 15–22 (1973)
43. Cardone, D.: Fragility curves and loss functions for RC structural components with smooth rebars. Earthq. Struct. **10**(5), 1181–1212 (2016)
44. Cardone, D., Perrone, G.: Developing fragility curves and loss functions for masonry infill walls. Earthq. Struct. **9**(1), 257–279 (2015)