

Vulnerability of Buildings

Subjects: Construction & Building Technology | Engineering, Civil | Architecture And Design

Contributor: Fatma Seyma Keskin

Vulnerability is defined for buildings as the degree of loss resulting from a hazard at a certain severity level and depends on the reduction in resistance and the level of decay in the structures as a result of constant exposure to environmental factors (such as seismic actions).

vulnerable buildings structural strengthening environmental sustainability life cycle
 environmental assessment embodied carbon embodied energy resource use

1. Background

Earthquakes are considered as the deadliest phenomena [1], as their occurrence collapses vulnerable buildings, therefore causing high numbers of casualties [2]. To increase the resistance of buildings, they would naturally need to meet upgraded safety requirements. However, the necessary progress for pre-disaster preparedness, including the renewal of building codes, is far behind in developing countries compared to developed countries [2]. Added to that, post-disaster preparedness is also rare in these countries [3]. A third factor to consider is the fact that population growing trends concentrate in megacities, while projections spanning the next 50 years suggest that one earthquake event in one such a city may cause up to 1 million deaths [4], hence our suggesting that current vulnerable building stock will increase exponentially.

The environmental sustainability of the buildings adds problems once the building sector is highly responsible for world energy consumption and carbon dioxide (CO₂) emissions. While the total energy use during the operation and construction of the building sector has reached 36% of global final energy use, CO₂ emissions from buildings have generated about 40% of the world's total emissions [5]. For instance, greenhouse gas (GHG) emissions are one of the sources of air pollution, and buildings are individually responsible for more than half of emissions by the built environment. This air pollution caused by energy use in buildings globally kills half a million each year [6]. To an extent, this latent problem reflects the inability of construction industries in keeping up or engaging with other sectors in developing and enforcing sustainability methods and procedures. In such a context, energy-efficient measures and the efficient use of resources (building materials) offer opportunities for reducing emissions [7], while life cycle assessment (LCA) frameworks provide tools and instruments to quantify environmental impacts, taking into account lifetime flows between nature and building from cradle-to-grave [8].

2. State of the Art of the Life Cycle Environmental Impact Assessment of Vulnerable Buildings

Buildings consume energy and emit pollutants throughout their entire life. This occurs through embodied and operational energy and carbon. Embodied impacts span the manufacturing and end-of-life stages of a building, whereas operational impacts refer to its use [9]. Figure 1 illustrates this distinction through stages and system boundaries, including representative modules according to EN 15,978 [10] and Annex 57 [11]. Embodied impacts load the environment through resource depletion and the pollution of water, air and soil, and embodied energy can constitute 10–20% of the energy demand of a building from cradle-to-grave (regarding both residential and office buildings) [12]. Carbon emissions occur during manufacturing, on-site construction, repair, deconstruction, and mainly the construction stage because of the large energy consumption [13]; the manufacturing of building materials takes up about 20% of the world's fuel consumption [14]. Furthermore, the manufacturing phase depletes natural resources and generates significant amounts of debris from demolition. Evidence of this is the approximately 89 billion tons (Gt) of natural resources consumed in 2017 globally. The construction sector consumed 44 Gt from the global account of non-metallic materials, and this amount is set to increase to 86 Gt by 2060 [15]. This adds to the fact that the operation of buildings causes the highest energy consumption and accompanying GHG emissions amongst other human-led activities [16]. Therefore, most sustainability initiatives and techniques aim at cutting down the operational energy to nearly zero while excluding embodied energy.

Modern techniques for reducing energy and carbon emissions related to buildings focus on energy upgrading. This has revealed that existing building stock could not provide sufficient energy saving; most crucially, this expansive stock continues deteriorating, which increases vulnerability to seismic motions [17]. For this reason, Feroldi et al. [18], Mora et al. [19], Marini et al. [17], Georgescu et al. [20], Basirico and Enea [21], De Vita et al. [22], Mora et al. [23], and Lamperti et al. [24] have worked to increase structural safety through energy retrofitting mostly focused on building envelopes that provide thermal comfort.

However, these studies do not foresee merging the assessment of structural and environmental performance [25] while excluding the embodied carbon and energy caused by structural deficiencies in reported life cycle analyses.

As sustainability best practice manages to reduce operational energy, the research focus will slightly shift to tackle material-related embodied impacts [26]. To date, traditional LCA frameworks have been partially insufficient to assess a building's environmental performance accurately, particularly when environmental loss due to destructive disasters needs addressing [27]. It is worth noting that the quantification of building environmental impacts includes the entire process from construction to maintenance and replacements [28]. However, no equivalent database exists for the environmental impacts of post-disaster repair or the reconstruction of buildings in the historical loss data in the form of cost data associated with damage repair [1]. As a result, various studies have estimated the environmental impacts derived from the repair probabilistically. These are mostly focused on seismic damage, and therefore integrate performance-based earthquake engineering (PBEE) methods [29]. These use HAZUS and/or PACT tools to calculate earthquake-induced losses probabilistically, considering uncertainties associated with seismic events, relate damage probabilities [30][31] and relevant repair costs that can be adopted to calculate environmental impacts [32]. This adoption has been conducted through three different pathways [29], namely, repair cost ratio (ratio between repair cost and replacement cost of a building) [33][34][35][36], EIO-LCA (economic input-output life cycle assessment) [37][38], and LCA according to repair description [1][2][28][32][39][40][41][42][43][44][45][46]. In recent years, the integration methods and standards have increased substantially; however, no consensus has been created on the best-integrated approach [29]. Part of the complexity of finding the optimal approximation is the need to fulfil hazard-resistant design [42], which tends to be a highly technical subject compared with standard LCA. The hazard-resistant design should also cover pre- and post-disaster construction and repair for existing vulnerable buildings.

Due to retrofitting of post-disaster buildings being characterized by an extended lifespan, including versatile and adaptable design procedures and solutions, data collection, and interpretations [42], existing probabilistic assessments may not be sufficient for the sustainable transformation of existing vulnerable buildings. At this point, real-world applications of retrofitting can be investigated to assess their environmental impacts [34]. Some studies [43][47][48][49][50][51][52][53][54] focused on structural retrofitting of the existing building and their environmental impacts. Some [25][55] combine structural and sustainability metrics with economic terms implemented by monetizing CO₂ emissions. These studies are inherently specific to a particular region and seismic events, which makes them difficult to use elsewhere, as building performance objectives may vary, or conversely, performance-based standards may target different objectives [30]. The process of recovering existing buildings requires integrated multidisciplinary approaches; hence it is crucial to identify ongoing interactions [22]. Existing buildings provide a great advantage to avoid new environmental impacts. Since they have already released embodied carbon during their construction, keeping them in service for as long as possible helps to amortize this carbon debt by avoiding new emissions from demolition or new building construction [8]. Added to this, the multiple deficiencies that characterize vulnerable infrastructure demand better insight into the new resilience target in response to a disaster. In this study, these deficiencies are scrutinized from an environmental sustainability perspective to understand the life cycle impacts of vulnerable buildings, considering extended and designed service periods. Therefore, an integrated method is developed that gives a simplified and improved framework based on alternative scenarios considering different damage scales and local codes for structures, including Pre-LCA and LCA stages.

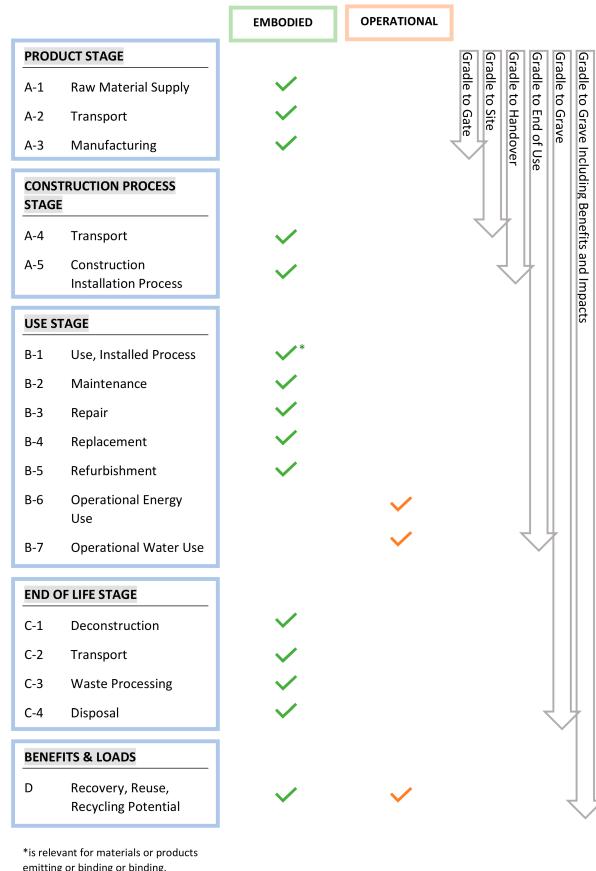


Figure 1. Embodied and operational impacts over building life cycle stages [10][56].

References

1. Wei, H.-H.; Shohet, I.M.; Skibniewski, M.J.; Shapira, S.; Yao, X. Assessing the lifecycle sustainability costs and benefits of seismic mitigation designs for buildings. *J. Archit. Eng.* 2016, 22, 4015011.
2. Bhattacharya, S.; Nayak, S.; Dutta, S.C. A critical review of retrofitting methods for unreinforced masonry structures. *Int. J. Disaster Risk Reduct.* 2014, 7, 51–67.
3. Tucker, B.E. Reducing Earthquake Risk. *Science* 2013, 341, 1070–1072.
4. Bilham, R. The seismic future of cities. *Bull. Earthq. Eng.* 2009, 7, 839–887.
5. IEA International Energy Agency. Energy Efficiency: Buildings. Available online: <https://www.iea.org/topics/energyefficiency/buildings/> (accessed on 7 September 2019).
6. C40 Cities. The Net Zero Carbon Buildings Declaration. Available online: <https://www.c40.org/other/net-zero-carbon-buildings-declaration> (accessed on 7 November 2020).
7. UN. Emissions Gap Report 2019; UN: New York, NY, USA, 2019.
8. O'Connor, J. What Can We Do about Embodied Carbon? *Canadian Architect*: Toronto, ON, Canada, 2020; pp. 36–39.
9. Chastas, P.; Theodosiou, T.; Bikas, D. Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. *Build. Environ.* 2016, 105, 267–282.
10. BS EN 15978, Sustainability of Construction Works, Assessment of Environmental Performance of Buildings: Calculation Method. Available online: <https://standards.iteh.ai/catalog/standards/cen/62c2cef-5666-4719-91f9-c21cb6aa0ab3/en-15978-2011> (accessed on 7 September 2021).
11. International Energy Agency. Guideline for Design Professionals and Consultants Part 1: Basics for the Assessment of Embodied Energy and Embodied GHG Emissions Energy in Buildings and Communities Programme; International Energy Agency: Paris, France, 2016.

12. Ramesh, T.; Prakash, R.; Shukla, K.K. Life cycle energy analysis of buildings: An overview. *Energy Build.* 2010, 42, 1592–1600.
13. Shrivastava, S.; Chini, A. Estimating energy consumption during construction of buildings: A contractor's perspective. In Proceedings of the World Sustainable Building Conference, Helsinki, Finland, 18–21 October 2011; pp. 18–21.
14. Dixit, M.K.; Fernández-Solís, J.L.; Lavy, S.; Culp, C.H. Identification of parameters for embodied energy measurement: A literature review. *Energy Build.* 2010, 42, 1238–1247.
15. OECD. Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences; OECD: Paris, France, 2018.
16. Rajagopalan, N.; Bilec, M.M.; Landis, A.E. Life cycle assessment evaluation of green product labeling systems for residential construction. *Int. J. Life Cycle Assess.* 2012, 17, 753–763.
17. Marini, A.; Passoni, C.; Belleri, A.; Feroldi, F.; Preti, M.; Metelli, G.; Riva, P.; Giuriani, E.; Plizzari, G. Combining seismic retrofit with energy refurbishment for the sustainable renovation of RC buildings: A proof of concept. *Eur. J. Environ. Civ. Eng.* 2017, 1–21.
18. Feroldi, F.; Marini, A.; Badiani, B.; Plizzari, G.A.; Giuriani, E.; Riva, P.; Belleri, A. Energy efficiency upgrading, architectural restyling and structural retrofit of modern buildings by means of “engineered” double skin façade. In Proceedings of the 2nd International Conference on Structures & Architecture (ICSA2013), Guimaraes, Portugal, 24–26 July 2013; pp. 1859–1866.
19. Mora, T.D.; Righi, A.; Peron, F.; Romagnoni, P. Functional, Energy and Seismic Retrofitting in Existing Building: An Innovative System Based on xlam Technology. *Energy Procedia* 2015, 82, 486–492.
20. Georgescu, E.-S.; Georgescu, M.; Macri, Z.; Marino, E.; Margani, G.; Meita, V.; Pana, R.; Cascone, S.; Petran, H.; Rossi, P.; et al. Seismic and Energy Renovation: A Review of the Code Requirements and Solutions in Italy and Romania. *Sustainability* 2018, 10, 1561.
21. Basiricò, T.; Enea, D. Seismic and energy retrofit of the historic urban fabric of Enna (Italy). *Sustainability* 2018, 10, 1138.
22. De Vita, M.; Mannella, A.; Sabino, A.; Marchetti, A. Seismic Retrofit Measures for Masonry Walls of Historical Buildings, from an Energy Saving Perspective. *Sustainability* 2018, 10, 984.
23. Mora, T.D.; Pinamonti, M.; Teso, L.; Boscato, G.; Peron, F.; Romagnoni, P. Renovation of a school building: Energy retrofit and seismic upgrade in a school building in Motta Di Livenza. *Sustainability* 2018, 10, 969.
24. Lamperti Tornaghi, M.; Loli, A.; Negro, P. Balanced Evaluation of Structural and Environmental Performances in Building Design. *Buildings* 2018, 8, 52.
25. Loli, A.; Lamperti Tornaghi, M.; Negro, P. A method to include life-cycle analysis in earthquake design. In Proceedings of the 16th World Conference on Earthquake Engineering, Santiago, Chile, 9–13 January 2017.
26. Rossi, B.; Marique, A.-F.; Reiter, S. Life-cycle assessment of residential buildings in three different European locations, case study. *Build. Environ.* 2012, 51, 402–407.
27. Wei, H.-H.; Skibniewski, M.J.; Shohet, I.M.; Yao, X. Lifecycle Environmental Performance of Natural-Hazard Mitigation for Buildings. *J. Perform. Constr. Facil.* 2016, 30, 04015042.
28. 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.* 2013, 18, 504–515.
29. Hasik, V.; Chhabra, J.P.S.; 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.* 2018, 175, 123–137.
30. Applied Technology Council for the Federal Emergency Management Agency. Techniques for the Seismic Rehabilitation of Existing Buildings; Applied Technology Council for the Federal Emergency Management Agency: Washington, DC, USA, 2006; Volume FEMA 547.
31. Applied Technology Council for the Federal Emergency Management Agency. Next-Generation Methodology for Seismic Performance Assessment of Buildings; Applied Technology Council for the Federal Emergency Management Agency: Washington, DC, USA, 2012; Volume FEMA P-58.

32. Welsh-Huggins, S.J.; Liel, A.B. A life-cycle framework for integrating green building and hazard-resistant design: Examining the seismic impacts of buildings with green roofs. *Struct. Infrastruct. Eng.* 2017, 13, 19–33.
33. Chiu, C.K.; Chen, M.R.; Chiu, C.H. Financial and Environmental Payback Periods of Seismic Retrofit Investments for Reinforced Concrete Buildings Estimated Using a Novel Method. *J. Archit. Eng.* 2013, 19, 112–118.
34. Feese, C.; Li, Y.; Bulleit, W.M. Assessment of Seismic Damage of Buildings and Related Environmental Impacts. *J. Perform. Constr. Facil.* 2015, 29, 04014106.
35. Padgett, J.E.; Li, Y. Risk-Based Assessment of Sustainability and Hazard Resistance of Structural Design. *J. Perform. Constr. Facil.* 2016, 30, 04014208.
36. Alirezaei, M.; Noori, M.; Tatar, O.; Mackie, K.R.; Elgamal, A. BIM-based Damage Estimation of Buildings under Earthquake Loading Condition. *Procedia Eng.* 2016, 145, 1051–1058.
37. Comber, M.V.; Poland, C.D. Disaster Resilience and Sustainable Design: Quantifying the Benefits of a Holistic Design Approach. In Proceedings of the Structures Congress, Pittsburgh, PA, USA, 2–4 May 2013; American Society of Civil Engineers: Reston, VA, USA, 2013; pp. 2717–2728.
38. 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. In Proceedings of the Structures Congress, Portland, OR, USA, 23–25 April 2015; American Society of Civil Engineers: Reston, VA, USA, 2015; pp. 933–944.
39. Welsh-Huggins, S.J.; Liel, A.B. Evaluating Multiobjective Outcomes for Hazard Resilience and Sustainability from Enhanced Building Seismic Design Decisions. *J. Struct. Eng.* 2018, 144, 04018108.
40. Simonen, K.; Huang, M.; Aicher, C.; Morris, P. Embodied carbon as a proxy for the environmental impact of earthquake damage repair. *Energy Build.* 2018, 164, 131–139.
41. Sarkisian, M.P. Design of environmentally responsible structures in regions of high seismic risk. *Struct. Infrastruct. Eng.* 2014, 10, 849–864.
42. Welsh-Huggins, S.J.; Liel, A.B. Integrating hazard-induced damage and environmental impacts in building life-cycle assessments. In Proceedings of the 2014 International Symposium of Life-Cycle Civil Engineering, Tokyo, Japan, 16–19 November 2014.
43. Belleri, A.; Marini, A. Does seismic risk affect the environmental impact of existing buildings? *Energy Build.* 2016, 110, 149–158.
44. Hossain, K.A.; Gencturk, B. Life-Cycle Environmental Impact Assessment of Reinforced Concrete Buildings Subjected to Natural Hazards. *J. Archit. Eng.* 2016, 22, A4014001.
45. Gencturk, B.; Hossain, K.; Lahourpour, S. Life cycle sustainability assessment of RC buildings in seismic regions. *Eng. Struct.* 2016, 110, 347–362.
46. Chhabra, J.P.S.; 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. Archit. Eng.* 2018, 24, 04017035.
47. Menna, C.; Caruso, M.C.; Asprone, D.; Prota, A. Environmental sustainability assessment of structural retrofit of masonry buildings based on LCA. *Eur. J. Environ. Civ. Eng.* 2016, 1–10.
48. Terracciano, G.; Di Lorenzo, G.; Formisano, A.; Landolfo, R. Cold-formed thin-walled steel structures as vertical addition and energetic retrofitting systems of existing masonry buildings. *Eur. J. Environ. Civ. Eng.* 2015, 19, 850–866.
49. Napolano, L.; Menna, C.; Asprone, D.; Prota, A.; Manfredi, G. LCA-based study on structural retrofit options for masonry buildings. *Int. J. Life Cycle Assess.* 2015, 20, 23–35.
50. Ferreira, J.; Duarte Pinheiro, M.; de Brito, J. Economic and environmental savings of structural buildings refurbishment with demolition and reconstruction—A Portuguese benchmarking. *J. Build. Eng.* 2015, 3, 114–126.
51. Vitiello, U.; Salzano, A.; Asprone, D.; Di Ludovico, M.; Prota, A. Life-cycle assessment of seismic retrofit strategies applied to existing building structures. *Sustainability* 2016, 8, 1275.
52. Formisano, A.; Chiumiento, G.; Di Lorenzo, G.; Landolfo, R. Innovative and traditional seismic retrofitting techniques of an existing RC school building: Life cycle assessment and performance ranking through the

TOPSIS method. *Constr. Met.* 2017, 84–93. Available online: https://www.researchgate.net/publication/316845993_Innovative_and_traditional_seismic_retrofitting_techniques_of_an_existing_RC_structures (accessed on 7 September 2021).

53. Uzun, E.T.; Secer, M. Evaluation of Building Retrofitting Alternatives from Sustainability Perspective. *Procedia Eng.* 2017, 171, 1137–1146.

54. Ribakov, Y.; Halperin, I.; Pushkar, S. Seismic Resistance and Sustainable Performance of Retrofitted Buildings by Adding Stiff Diaphragms or Seismic Isolation. *J. Archit. Eng.* 2018, 24, 04017028.

55. Dattilo, C.; Negro, P.; Landolfo, R. An Integrated Approach for Sustainability (IAS): Life Cycle Assessment (LCA) as a Supporting Tool for Life Cycle Costing (LCC) and Social Issues. In Proceedings of the International Conference on Sustainable Building and Affordable To All, Algarve, Portugal, 17–19 March 2010; pp. 721–728.

56. Lützkendorf, T.; Balouktsi, M.; Frischknecht, R. Evaluation of Embodied Energy and CO₂eq for Building Construction (Annex 57), Subtask 1: Basics, Actors and Concepts; International Energy Agency: Paris, France, 2016.

Retrieved from <https://encyclopedia.pub/entry/history/show/33356>