Environmental LCA for maintenance and rehabilitation activities on structures under risk: a literature review

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Abstract

Under risk of hazardous events, which decreases the functionality of the system, the performance of structures and infrastructures have a crucial role on the sustainability that is characterized in terms of economic, environmental and social indicators. Decision makers who are responsible of taking decisions for the service provision in the system, face with several uncertainties. In order to decrease some of these uncertainties, Life Cycle Assessment (LCA) is one of the approaches which provides a framework to describe and analyze environmental impacts of hazardous events on a system (or a component of a system) or a product in all life cycle. This study presents a literature review to support decision makers for the alternatives of maintenance and rehabilitation activities on structures. The reviewed papers involve also the reconstruction of the structures to compare the environmental impacts of the results of the decisions.

1. Introduction

During the service life, every structure performs under certain risks which can originate due to sudden exposures (hazards) such as operations, natural hazards (e.g. earthquakes, floods, hurricanes etc.), contingencies or mishaps due to humans as well as it can be formed gradually from climatic changes, environmental effects (e.g. corrosion) or deterioration due to aging; and experiences damage on structures or structural elements or destruction of the environment.

In the face of hazards, structures' sustainability performances can be defined in terms of economic impacts e.g. business disruption, cost for repair activities; social impacts e.g. number of fatalities and injuries, affected population etc.; and environmental impacts e.g. pollution due to removing and demolishing the damaged components, debris disposal and repair works etc. For instance, in 2011 Great East Japan earthquake, economic impact was US $122 billion, social impact was more than 15-thousands of deaths and economic impact was 26,3 million tons of CO_2 equivalent emissions generated due to the recovery works (Wei et al 2016).

Decision makers (i.e. authorities in national and local level, asset owners, managers/operators) experience several uncertainties during the life cycle of the assets, especially when a natural or anthropogenic hazard is in the question. The concerns of the decision maker are to optimize investments into preventive measures, to limit the consequences in terms of economic, environmental, and social, to rehabilitate the losses and to reorganize the system.

In case of a hazardous event, it is important to prioritize the efficient and informed decision making (JCSS, 2008) at local levels in order to provide sustainable development at global scale. The traditional performance-based engineering assessment do not consider the environmental aspects i.e. during construction and operation, under a natural hazard, in the recovery phase namely repair and reconstruction activities or directly end of life. In order to consider environmental effects of these activities, Life Cycle Assessment (LCA) is one of the approaches. In ISO 14040:2006, LCA is defined as the methodology to quantify the potential impacts of a product system during its service life. When a physical structure is taken into account, a product system is the structure itself and the potential impacts can be thought on environment during maintenance activities before any hazardous event or repair and reconstruction activities after a hazardous event occurred.

Wei et al. (2015 and 2016) state that in literature there is a gap of study related with the rehabilitation of buildings against hazardous events and the environmental impacts associated with construction and operation phases.

The aim of this paper is to understand whether the maintenance activities applied to conserve the structure and limit the consequences before any hazardous event (e.g. earthquake, corrosion, degradation due to aging etc.); or repair and reconstruction activities in the after event phase performed on the structure has better results by considering specifically the environmental impacts. The authors' intention is not to show a comparative result, but to present a portfolio analysis to decision makers of the application of LCA on different case studies. In this paper, the literature is reviewed through representing the studies carried out related with environmental impacts of interventions performed on structure by using LCA approach, their cost and benefit analysis and usability of LCA approach in decision making process for the management purposes.

2. Method

In accordance with the aim of reviewing literature on environmental LCA for maintenance and rehabilitation activities under risks (specifically seismic risk), Scopus database has been utilized. Key words of "life cycle assessment" "maintenance" and "seismic" have been selected between the years of 2010 and 2019. There are 35 articles found and 7 related articles (articles and conference papers) have been reviewed. The 'review' papers are excluded from this study. Moreover, "life cycle assessment" and "seismic retrofit" keywords have been searched in Scopus in order to review other hazardous events related papers. Three articles have been found and one is taken under review.

Parameters that are studied in this paper are functional unit, life-span, environmental indicators and results of the analysis which can support (or not) the decision makers.

3. Analysis and results

3.1. Functional unit and life span

Functional unit is defined in ISO 14040:2016 as "quantified performance of a product system for use as a reference unit". In the reviewed 8 papers, three of them use one square meter, 1 paper uses 1 square foot, 1 paper considers 1 building which provides 20,903 m^2. In the other 3 papers, the functional unit is not defined clearly and the results in these papers are represented by percentages.

The life span parameter differs between papers reviewed. For the ordinary buildings 50-year life span is considered while for the historical structures the authors haven't mentioned of any specific life span since the all structures have been present since more than 50 years.

3.2. Goal and scope

The goal of an LCA states the intended application, reason and intended audience while the scope involves the functional unit, the system boundaries, limitations and impact categories (ISO 14040:2016). In this study the papers reviewed consist of different types of structures which are ordinary structures (e.g. residential and office buildings, bridge and schools) or historical structures with different type of use.

Padgett and Tapia (2013) consider bridge structure is a metasystem which involves materials, equipment, machinery and/or rerouted traffic and each of these components of the metasystem have their own lifecycles. Their aim is to provide environmental indicators for sustainability of structures which are experiencing several threats (e.g. deterioration and natural hazard risks) and to evaluate the impact of seismic retrofit on lifetime sustainability a seismically deficient bridge.

Two papers focus on the historical structures which are deteriorating in time. In the research of Garavaglia et al (2018), the case study is a pig abattoir which was built in 1902 and abandoned 1984. They aim to investigate the deterioration process of the structure, how the deterioration affects the system and which intervention scenarios are better for the structure without damaging architectural integrity. In the paper of Ferreira et al (2015), the historical structure built in 17^{th} century and the authors search whether the refurbishment or reconstruction of the deteriorating structure present in seismic zone is more convenient in terms of economic and environmental aspects. The case study selected is a cultural heritage structure in Portugal.

In the other 5 articles, three of them analyze reinforced concrete buildings (Chiu et al., 2012; Wei et al., 2016, 2015), steel and concrete buildings are compared in (Feese et al., 2015) and single steel structure is studied in (Chhabra et al., 2017). Chiu et al. (2012) investigate the financial and environmental paybacks of seismic retrofitting for low-rise RC buildings. They have selected the project of sixteen school buildings in Taiwan as case study.

The goal of the study of Wei et al (2015) is to perform a cost benefit analysis to assess the sustainability of two retrofit designs while considering the uncertainty of seismic events. A single RC building is studied. Moreover, in Wei et al (2016) the goals are to develop an LCA framework which can contain building damage and convert into environmental impact during both pre-seismic structural retrofitting and post-seismic rehabilitation; and to evaluate environmental value of the hazard mitigation. The case studies are one single RC building and seismic retrofitting in regional scale.

Feese et al. (2015) evaluate and compare the performance of steel and concrete buildings by considering their life cycle assessments and earthquake resistance (subjected to same earthquake event). Lastly, the research of Chhabra et al. (2017) estimates the functional life of the 9-story steel office building by considering multiple event scenarios. Also, it assesses the environmental impacts due to seismic hazard and repair activities in different building components.

3.3. **System boundaries**

The system boundaries defined by ISO 14040:2016 as "set of criteria specifying which unit processes are part of a product system". Padgett and Tapia (2013) have proposed a framework which can be used for life cycle environmental sustainability assessment for deteriorating bridge structures associated with construction, operation, maintenance, possible natural hazard exposure in the remaining service life and demolition. In this study, authors do not consider the operation phase (e.g. signage and lighting) in sustainability assessment since hazard mitigation is emphasized. In the analysis, the authors take into account also the transportation, namely extra distance due to the alternative route during retrofitting activities performed related with deterioration of the aging bridge structure and found that rerouting takes the big part of the expected sustainability metrics.

Similar to this Wei et al. (2015) have defined building life cycle with construction, operation, retrofit, rehabilitation and end-of-life phases, however the operation and end-of-life have not been analyzed since their environmental impacts are not affecting the structural behavior under seismic risk. Moreover, Ferreira et al. (2015) express that since in their study the structural issues are concerned, operation and maintenance impacts are neglected.

Chiu et al. (2013) work on seismic retrofitting of reinforced concrete buildings by dividing damage states to five i.e. without any damage, slight damage, medium damage, serious damage and total damage (including demolishing and disposal).

Garavaglia et al. (2018) are presenting a probabilistic approach of life cycle and rehabilitation activities for deteriorating structures, in terms of performance and cost. Their method simulates combined deterioration process, structural response and performance in time. In like manner, Wei et al. (2016) consider building life cycle consisting of hazard mitigation, operation and maintenance (not calculated), hazard exposure (involving demolition, debris removal, repair and transportation) and end-of-life (not calculated) phases.

Last but not least, Chhabra et al. (2018) and Feese et al. (2015) use different structural components as their boundaries to analyze environmental performance and impacts. Specifically in Chhabra et al. (2018) it has been found that the approach considers the multiple seismic events with the possibility of collapse or irreplaceable damage in functional life.

3.4. Environmental impact indicators

Almost all the papers account for the environmental impacts (except (Garavaglia et al., 2018)). In the six papers, authors used CO_2 emission as environmental indicators. The three of these papers used Global Warming Potential (GWP) which is calculated as CO_2 equivalent (Chhabra et al., 2018; Feese et al., 2015; Ferreira et. al 2015). Moreover, in the paper of Ferreira et. al (2015), environmental impact indicators that they take into consideration are GWP (kg CO_2 eq.), ozone layer depletion (kg CFC_{11} eq.), acidification potential (kg SO_2 eq.), eutrophication potential (kg $PO_4^{3-}PO_4^{3-}$), primary energy (MJ), waste generated (tone), groundwater replenishment indicator (mm/m^2).

The whole life cycle of a building is divided in two phases as embodied and operational energy. The embodied energy originates from the energy consumed during construction including transportation, manufacturing, technical installations and waste disposal activities. While the operational energy is the one needed for maintenance and use of energy, water, air-conditioning etc. (Wei et al. 2015). Padgett and Tapia (2013) include embodied energy (MJ/day) to their study with CO_2 emission (kg/day).

In two papers, the authors look at social and economic indicators ((Wei et al. 2016; Feese et al. 2015)). Wei and colleagues (2016) consider repair and replacing costs of damaged buildings as economic metrics, CO_2 emission which arise from repair activities as environmental metrics, number of deaths for social metrics. Feese et al (2015) the damage cost and money saved by upgrading design levels.

3.5. Results

In the reviewed papers, all authors found that the impacts of rehabilitation, maintenance and repair activities are less impactful on environment than the reconstruction activities (including demolishment of existing structure and debris removal).

Chhabra et al (2018) found that environmental impacts due to seismic related repairs over the functional life for non-structural components contributes to 262,035 kg CO_2 eq. (mean value) whereas structural components contribute 1,587 kg CO_2 eq. (mean value) which is equivalent to 3% of total replacement. Thus, they have stated that according to their research which is a probabilistic research with multiple earthquake scenarios, environmental impacts due to the repair activities after seismic event are more due to the damage on non-structural components such as plumbing and mechanical components etc. while the structural components contribute less to the total impact on the environment.

In another paper, it has been found that expected embodied energy and CO_2 emission of as-built are much more than retrofitted structure for 50-year remaining life (Padgett and Tapia 2013). Although, the authors found that the retrofitting reduces expected embodied energy CO_2 emission, the maintenance is more sustainable and effective measure. By retrofitting, it is obtained 69% of embodied energy savings and 66% of CO_2 emission savings. Repairs are stated as the most energy and emission consuming. The structural retrofitting activities support reducing the need of repair on bridge structures.

In study of Ferreira et al. (2015), the difference between refurbishment and new construction is 19,56 kg/ m^2 of CO_2 eq. (13%) in global warming potential and 10% in primary energy. In addition, the most significant savings are in waste production and eutrophication potential, difference of 266% and 542% respectively.

For the disused historical structure (in other words abandoned deteriorating existing structure) (Garavaglia et al 2018), it has been found that the repair of damaged elements is more favorable than the replacement of the entire structure in their case study. Between their results, it is stated that during the service life, each structural element loses 27% of the volume due to aging and use. After the roof collapse due to weathering and negligence in 1985, the loss in volume was almost 35%. Moreover, they found that probability of failure in 2015 is two order of magnitude more than the probability failure of 1984. This is why the authors specify the urgency of intervene on this deteriorating structure by preventative measure before any hazardous event occurs (Garavaglia et al 2018).

Wei et al (2015) divided the retrofit activities according to damage state i.e. slight, moderate, extensive and complete. The repairing activities consume 1.1% of construction emission (in terms of CO_2) at a state of slight damage; 7,3% at moderate damage state; 45% at extensive damage state and 100% when the structure has complete damage. Moreover, when it is coupled with emissions from demolition and debris removal, then it arrives to 118% approx. Thus, the prevention is the most effective mitigation strategy for the buildings which are possibly entering to the complete damage state in a possible earthquake. Also, Chiu et al (2013) have found that damage state and CO_2 emission of repair activities are directly correlated, and CO_2 emission of a seismic retrofitting activity is about 11% of the CO_2 emission of construction of a new building.

In terms of cost, three papers presented the results. Wei et al. (2016) have found that over a 20-year planning, total monetary benefits derived from reduction in fatalities, repair costs and CO_2 emissions are more than $100 thousand as results of retrofitting. Besides Ferreira et al. (2015) consider seismic strengthening with steel structure for historical structure. Since it is an expensive material, the cost of refurbishment is higher (approx. 58%) than the new construction which is done by reinforced concrete. Moreover, Feese et al. (2015) specify that upgrading design code for the steel structure from moderate to high design level contributes $843 of saving as well as $2779 of savings for the concrete building.

4. **Conclusions**

This paper has outlined the application of LCA method for the environmental assessment of maintenance and rehabilitation activities on structures that are under the risk of any probable events (including deterioration). The building types have not been limited by the material properties such as steel or concrete; type of structure; or intended use. Also, some examples for historical structure have been studied in order to understand the decision making on intervention activities for specifically historical structures. The aim of this paper is to investigate if the maintenance activities performed on structure in before event phase is better than the reconstruction of the structure considering specifically the environmental impacts when any possible hazardous event (i.e. natural, anthropologic or slowly impacting hazard such as deterioration) is taken into account. In all papers, it has been found that refurbishment and maintenance activities performed before any hazardous event are more efficient in terms of environmental sustainability than the repair activities performed in after event phase. In addition, the least profitable activity can be performed is rebuilding a new structure after the severe damage or collapse. However, the studies are found very different from each other and they are not equated.

It has been found that for historical structures, maintenance (or repair since it is already under deterioration effect) activities are recommended both to preserve the integrity of the structure and to prevent the environmental impacts. However, the performance of the repair activities requires more attention and more financial resources in case it is a cultural heritage structure under protection.

In this research, the reviewed studies are not compared with each other, since the aim is to represent a portfolio of application of LCA for different structures with various material, age and design properties. By using LCA it is possible to take decisions for the maintenance activities on structures. It has been obtained that LCA is an efficient method for the risk-based decision making under uncertainty since it allows to compare the environmental and economic impacts of different intervention activities performed on a structure. LCA can be also done in the before event phase to allocate the resources for the intervention planning of the structures during their service life.

5. **Appendix**

Table 1 Articles reviewed in this study

Articles	Goal and Scope	Functional unit	Environmental indicators	Findings
Feese et al 2015	Evaluates and compares the performance of steel and concrete buildings by considering their life cycle assessments and earthquake resistance (subjected to same earthquake event).	1 square foot	GWP (ton CO_2 eq./square foot Fossil Fuel consumption (total energy) (MJ/square foot)	Total LCA environmental impact (MJ/square foot) [data from Athena 2013] -steel: 8,949 -concrete: 9,048
Padgett and Tapia 2013	To quantify sustainability performance indicators for a seismically deficient bridge and to evaluate the impact of seismic retrofit on lifetime sustainability.	-	Embodied energy and CO_2 emission	69% of embodied energy savings and 66% of CO_2 emission savings
Wei et al 2016	The aims are 1) to develop an LCA framework which can contain building damage and convert into environmental impact during both pre-seismic structural retrofitting and post-seismic rehabilitation; 2) to evaluate environmental value of the hazard mitigation. The case studies are selected as one single RC building and seismic retrofitting in regional scale.	● 1 m^2 ● number of fatalities per building for the social metric, ● the amount of money per square meter of a building ($/m2) for the economic metric, ● the amount of CO_2 per square meter of a building (CO_2/m^2) for the environmental metric.	CO_2 emission (kg/m^2)	More than $100 thousand
Wei et al 2015	The goal is to perform a cost benefit analysis to assess the sustainability of two retrofit designs while considering the uncertainty of seismic events. A single RC building is studied.	the amount of CO_2 per square meter of a building (CO_2/m^2)	CO_2 emission (kg/m^2)	Damage states; 1-slight (1,1%) 2-moderate (7,3 %) 3-extensice (45%) 4-total (118% with demolition and debris removal)
Chiu et al 2013	Financial and environmental impacts of seismic retrofitting for low-rise RC buildings.	-	CO_2 emission	11% of CO_2 emission of new building
Chhabra et al 2018	It estimates the functional life of the 9-story steel office building by considering multiple event scenarios. Moreover, it assesses the environmental impacts due to seismic hazard and repair activities in different building components.	1 building providing 20,903 m^2 of office space	GWP (kg CO_2 eq.)	Global warming potential due to repair actions over the functional life: 263,622 kg CO_2 eq. (=3% of total replacement) The total replacement of building 8,220,774 kg CO_2 eq.

Articles	Goal and Scope	Functional unit	Environmental indicators	Findings
Ferreira et al 2015	The aim is to answer whether the refurbishment activities or rebuilding the structure in seismic zones is more profitable for the historical structure. The case study is a cultural heritage structure in Portugal.	1 m^2 of construction	Environmental impacts that they take into consideration are GWP (kg CO_2 eq.), ozone layer depletion (kg CFC_{11} eq.), acidification potential (kg SO_2 eq.), eutrophication potential (kg $PO_4^{3-}PO_4^{3-}$), primary energy (MJ), waste generated (tone), groundwater replenishment indicator (mm/ m^2).	19,56kg/ m^2 CO_2 eq. (13% difference between reconstruction and refurbishment)
Garavaglia et al 2018	To investigate the deterioration process of the structure, how the deterioration affects the system and which intervention scenarios are better for the structure without damaging architectural integrity. They analyze the roof structure of a pig abattoir-historical structure.	-	-	Volume loss suffered over time: each structural element loose 27% of the volume due to aging and use.

6. References

Chhabra, J.P.S., Hasik, V., Bilec, M.M. and Warn, G.P., 2017. Probabilistic Assessment of the Life-Cycle Environmental Performance and Functional Life of Buildings due to Seismic Events. *Journal of Architectural Engineering*, 24(1), p.04017035.

Chiu, C.K., Chen, M.R. and Chiu, C.H., 2012. Financial and Environmental Payback Periods of Seismic Retrofit Investments for Reinforced Concrete Buildings Estimated Using a Novel Method. *Journal of Architectural Engineering*, 19(2), pp.112–118.

Feese, C., Li, Y. and Bulleit, W.M., 2015. Assessment of Seismic Damage of Buildings and Related Environmental Impacts. *Journal of Performance of Constructed Facilities*, 29(4), p.04014106.

Ferreira, J., Pinheiro, M.D. and De Brito, J., 2015. Economic and environmental savings of structural buildings refurbishment with demolition and reconstruction-A Portuguese benchmarking. *Journal of Building Engineering*, *3*, pp.114-126.

Garavaglia, E., Basso, N. and Sgambi, L., 2018. Probabilistic life-cycle assessment and rehabilitation strategies for deteriorating structures: a case study. *International Journal of Architectural Heritage*, [online] 12(6), pp.981–996. Available at: <https://doi.org/10.1080/15583058.2018.1431727>.

ISO 14040:2006. Environmental management — Life cycle assessment — Principles and framework.

JCSS, 2008. Risk assessment in engineering: principles, system representation & risk criteria., ETH Zurich: s.n.

Padgett, J.E. and Tapia, C., 2013. Sustainability of natural hazard risk mitigation: Life cycle analysis of environmental indicators for bridge infrastructure. *Journal of Infrastructure Systems*, *19*(4), pp.395-408.

Wei, H.-H., Shohet, I.M., Skibniewski, M.J., Shapira, S. and Yao, X., 2016. Assessing the Lifecycle Sustainability Costs and Benefits of Seismic Mitigation Designs for Buildings. *Journal of Architectural Engineering*, 22(1), p.04015011.

Wei, H.-H., Skibniewski, M.J., Shohet, I.M. and Yao, X., 2015. Lifecycle Environmental Performance of Natural-Hazard Mitigation for Buildings. *Journal of Performance of Constructed Facilities*, 30(3), p.04015042.