Vulnerability of Buildings

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Definition

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).

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 (CO_2) emissions. While the total energy use during the operation and construction of the building sector has reached 36% of global final energy use, CO_2 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].

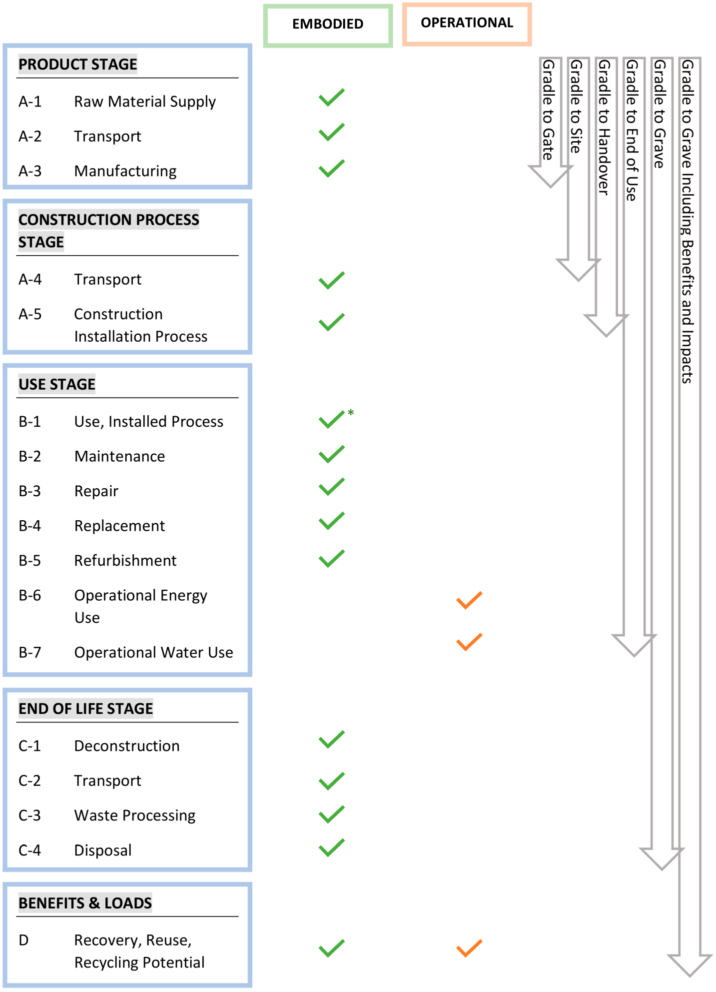
2. State of the Art of the Life Cycle Environmental Impact Assessment of Vulnerable Buildings

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][27][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 [47], 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 CO_2 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.



*is relevant for materials or products emitting or binding or binding.

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

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