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Optimization of Sustainability and Flood Hazard Resilience for Home Designs

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Abstract

Life-cycle analysis is a beneficial tool that can be utilized to quantify the performance of buildings within the context of environmental impact metrics (e.g. carbon footprint). While typical life-cycle analysis incorporates regular building maintenance, structural repairs made as a result of natural hazard damages are largely ignored. This study presents an environmental impact design optimization model that can be used to compare multiple coastal, single-family residential (SFR) building designs subjected to coastal flood hazards based on environmental impact factors. For each design, the model measures the environment impact (i.e. embodied energy and carbon footprint) of initial construction plus flood-induced repairs. Repairs are quantified using a probability-based methodology and life-cycle analysis is used to measure environmental impacts. Design options can then be compared and optimal designs that meet performance-based resilience and sustainable design objectives can be selected. A case study is presented for an SFR building located in coastal St. Petersburg, Florida, USA, and demonstrates that up to a 64% reduction in embodied energy and carbon footprint can be achieved over a 50 year building life through more resilient component configurations and materials and by increasing first floor elevations.

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Keywords: Resilience; Sustainability; Life-cycle Assessment; Residential

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1. Introduction

Life-cycle assessment or life-cycle analysis (LCA) is a commonly accepted methodology for objectively investigating the environmental impacts of products. In process-based LCA, the environmental impact of a product's lifecycle is determined by identifying the environmental flows (i.e., resources and emissions or wastes) within a defined system boundary of a product life-cycle. The product life-cycle is typically defined by four phases or stages; 1) acquisition of raw materials and material production, 2) manufacturing/construction, 3) use, reuse or/and maintenance, and 4) disposal/waste management, end-of-life, and/or recycling [1,2,3]. The methodology for LCA is outlined in the international standard ISO 14040.

Many have utilized LCA to estimate the environmental impacts of multi-family and SFR buildings [e.g. 4, 5, 6, 7]. While most residential LCA studies consider maintenance over the useful life of a building, the type of maintenance considered is not related to natural hazard related damage. Considering that almost 40% of the 2010 U.S. population lived in counties that constitute the shoreline of the country (10% of the total U.S. land area) [8] and that significant portions of coastlines are at risk from the effects future sea level rise [9, 10, 11] and increases in the frequency of stronger tropical cyclones [12], it is important to consider natural hazard damage when conducting LCAs of coastal, residential building designs.

More recent work [e.g. 13, 14, 15, 16, 17] has addressed the development of models for quantifying environmental impacts from earthquake damage-related repairs. In the studies that present case studies, multi-story reinforced concrete and steel structures in general are considered, which are more typical of commercial or multi-family residential construction, but SFR buildings have not received sufficient attention. Also, one study developed a framework for assessing the social, environmental and economic impacts associated with seismic and flood induced damages of reinforced concrete bridges [18], while another presented a model for assessing environmental impacts associated with damage from multiple hazards to bridges [19]. One study compared the environmental impacts of wind damage resulting from the use of either standard or hazard-resistant windows [20]. While these studies begin to weigh sustainable performance design objectives against hazard-resistant building designs, there is still a tremendous need to address coastal hazards within the context of SFR buildings.

This paper presents an environmental impact design optimization model that can be used to compare multiple coastal, single-family residential (SFR) building designs subjected to coastal flood hazards. For each design, the model measures the environment impact (i.e. embodied energy and carbon footprint) of initial construction plus repairs. Repairs are quantified using a probability-based procedure and life-cycle analysis is used to measure environmental impacts. A one-story home in Saint Petersburg, Florida, is evaluated as a case study to demonstrate the capability of the model for optimizing flood performance-based designs.

2. Flood Optimization Model Methodology

Environmental impact can be calculated using multiple metrics; however, for this study, environmental impacts are expressed in terms of embodied energy and global warming emissions (e.g. methane, carbon dioxide). Embodied energy is the estimated energy associated with producing a product and is expressed in units of energy (MJ). Global warming emissions (i.e. carbon footprint) are typically expressed in kg CO_2 equivalent (eq.), which includes an estimate of all global warming contributing emissions released in the production of a product. The flood model is designed to compare multiple designs to identify optimal performance by evaluating the environmental impact (embodied energy and CO_2 footprint) of initial construction and flood-induced repairs over the life of the building. The output of the optimization model is the selection of the design with the lowest total environmental impacts associated with the initial construction (C) and repairs (R).

The environmental impact of initial construction is calculated utilizing a life-cycle inventory (LCI) database, which provides the environmental impact per unit of material. The quantities of all materials used in the construction of the building are estimated and the impacts are calculated. Flood repairs are assessed using a lifecycle material damage estimator which simulates flood events (i.e. flood depths) over a building's design life utilizing Monte Carlo analysis and calculates the expected mean material repair quantities through a process of convolving the set of probable flood depths and the damage associated with those flood depths (Equation 1).