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A New Normative Workflow for Integrated Life-Cycle Assessment

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ABSTRACT

In order to curtail energy use by the building sector, consideration of how a "sustainable" building is constructed is paramount, in many respects, to how efficiently it operates over its lifetime. A typical building must be in use for decades before the energy expended in its daily operations surpasses the energy embodied within its initial construction, as a result of the materials used. More vitally: every building has specific vulnerabilities, particularly to hazards (e.g., earthquakes, wind, flooding) whose effects on sustainability are not explicitly considered alongside other aspects of sustainability in the design process – despite the significant environmental impact of damage and repairs after a disaster. Unfortunately, the joint consideration of resilience and sustainability in design is far from trivial, requiring various interdisciplinary perspectives involved in the delivery of building projects. These perspectives each contribute the models and data necessary for integrated evaluation, leading to the notorious challenges of BIM and data interoperability. In response, this paper presents a new end-to-end workflow for life-cycle assessment (LCA) of buildings that captures the dependencies between multi-hazard resilience and sustainability, across multiple dimensions of environmental impact. An illustrative example reveals how consideration of hazards during design and material selection influence embodied energy, ultimately revealing design choices that best achieve joint resiliency and sustainability.

KEYWORDS

Life Cycle Analysis, Natural Hazards, Resilience, Sustainability, Embodied Energy

INTRODUCTION

Buildings account for 40% of annual CO2 emissions in the United States, placing the building industry at the forefront of the growing international mandate to better steward our environment (Dixit et al., 2012). This has prompted the mainstreaming of sustainability assessments into project workflows, with efforts focused on optimizing operating energy. However, a typical building must be in use for decades before its operating energy surpasses the energy embodied in the extraction, processing, manufacture, delivery, repair and disposal of its constitutive materials (Sartori and Hestnes, 2007; Dixit et al., 2012). Additionally, energy expended in material and system repairs due to damage by natural hazards is often not explicitly considered in the design process. However, this evaluation is critical when one recognizes that each building's hazard vulnerabilities are driven by the unique choices of material assemblies that form the building's systems, components, and finishes. This demands an integrated approach to Life Cycle Assessment (LCA) wherein the vulnerabilities that drive hazard resilience can be included in a holistic environmental impact assessment.

Historically, the numerous disciplines involved in building projects have partitioned the analyses central to delivering such integrated LCAs, with each developing unique abstractions of the structure to simplify modeling requirements and fulfill design objectives. This limits interoperability between modeling environments and discipline-specific data sources, creating barriers in the joint evaluation of resilience and sustainability. However, by leveraging semantic data perspectives from computer science, one is able to efficiently bridge data structures and maintain the vocabularies normative to each domain's tools so they can interoperate. This research adopts such an approach, developing an automated framework for integrated LCAs. This framework is capable of capturing the dependencies between multi-hazard resilience and sustainability, across multiple dimensions of environmental impact, while maintaining the native modeling environments common to building practice. This paper presents a schematic representation of the resulting end-to-end workflow, including methodologies used to conduct its various analyses. An illustrative example building is presented to demonstrate the initial joint evaluation of resilience and sustainability, including the assessment of design alternatives.

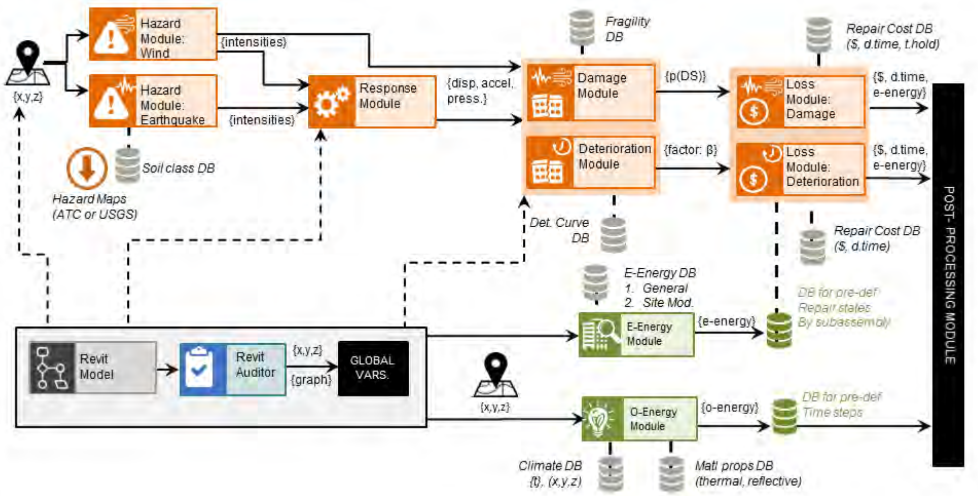

Figure 1. Schematic representation of proposed integrated life cycle analysis framework.

METHODOLOGY

The proposed integrated LCA (depicted in Figure 1) adopts a modularized approach to enable "best of breed" tools to be incorporated as they become available. The sequencing of operations in the LCA framework is now introduced for each of the integrated modules. While the framework conducts multi-hazard evaluations, specific focus is placed upon seismic hazards in the following description and subsequent example for brevity.

1. Primary user interfacing adopts the commercial software Revit©, due to its popularity in practice. The Revit model and building location are circulated into the **Revit Auditor,** which characterizes relevant geometries and creates an inventory of components using ontology-based data patterns (Ferguson et al., 2016a). This provides a queryable semantic "knowledge graph" of building information enabling the extraction of features and data required by subsequent modules.
2. The building location and dynamic properties are retrieved by the **Hazard Module**, which identifies the intensities for each natural hazard at different return periods, (e.g. 500-year event). For seismic hazards, spectral acceleration (e.g., 0.5 g) is used as the intensity measure to construct a hazard curve describing the degree of exposure (return period) at each intensity level (USGS, 2018). In this study, intensity selection effectively partitions the hazard curve into eight intervals.
3. These intensity measures and the corresponding building properties (e.g., floor to floor height and natural period) are utilized in the **Response Module** to calculate the building's engineering demand parameters (EDPs) over the building's intended service life (e.g., 50

years). For seismic hazards, EDPs (such as drift ratios and accelerations) are determined through a linear-elastic finite element analysis and FEMA (Federal Emergency Management Agency) P-58's Simplified Analysis Procedure (ATC, 2012).

4. The resulting EDPs are fed to the **Damage Module** to evaluate the vulnerabilities of building components due to hazard exposure. By explicitly representing each building assembly, those most driving resilience or sustainability performance can be identified, providing designers with insight about the broader impact of their design decisions. This is made possible through an assembly-based vulnerability approach (Porter et al., 2001), in which each assembly is comprised of a group of building components that share common vulnerability and cost characteristics. Vulnerabilities are defined using fragility curves, obtained from FEMA's Performance Assessment Calculation Tool (PACT), defined as the probability that an EDP will exceed a threshold defining acceptable structural performance. This provides a detailed damage assessment for each assembly. A parallel physics-based Deterioration Module (see Figure 1) considers service-induced wear, but is beyond the scope of this paper.
5. The **Loss Module** correlates these damages due to hazard exposure to a set of consequences (emphasis herein is on monetary costs, though downtime can also be determined) for various service lives. For this study, the direct seismic losses are evaluated considering the probability of incurring damage and relating this to the corresponding repair cost for each assembly (ATC, 2012; Cardone and Perrone, 2015). For consistency, initial cost of construction is based upon total replacement cost.
6. The embodied energy in the building's initial construction (EE:IC) and its operating energy are evaluated within the **Environmental Impact Module**. Operating energy is calculated through a lumped capacitance model which evaluates the heat flux using material and spatial properties (Ferguson et al., 2016b). It should be noted that plug loads are not included in operating energy calculations, though these can be easily accommodated in the future. Site-specific assessment of the building's operating energy is informed by climatology data from EnergyPlus (DOE, 2018). To determine the EE:IC, material volumes are calculated using the Revit Auditor and multiplied by each material's respective cradle-to-gate embodied energy and density (Hammond and Jones, 2011). Energy embodied in the repair materials (EE:RM) necessitated by hazard exposure is calculated by expressing the monetary cost of each assembly's repair as a percentage of the initial cost and multiplying that by the EE:IC of the assembly for a cradle-to-gate estimate.
7. These results are aggregated by the **Post-Processing Module,** which outputs embodied and operating energy as well as monetary losses by assembly as standard visualizations for different service lives. These assembly-based visualizations provide greater insight into the design choices that are most likely to improve the building's resilience and sustainability over different service lives.

ILLUSTRATIVE EXAMPLE

The integrated LCA framework is next applied to a building in Los Angeles employing a two-story reinforced concrete (RC) frame with concrete floor and roof slabs. The building consists of a regular floor plan, measuring 7 by 9 meters, with top-of-slab elevations at of 4.15 and 7.65 meters. The structural system of the building is a special moment resisting frame, as required for regions of high seismicity. The envelope consists of infill concrete masonry units (CMU) with a brick veneer. There are two interior partitions at each floor: gypsum wall board on metal stud. The following section presents the evaluation of this Initial Design from the joint perspective of sustainability and resilience using the proposed end-to-end LCA workflow. All results are described by assembly to reveal those which may warrant design revisions. To further demonstrate how such assembly-based insights can be used, two design alternatives are respectively evaluated: increasing the size of the columns in the special moment frame (termed Frame Upgrade) and selecting an Alternate Envelope using precast RC panels.

Figure 2. Annotated visualization of embodied energy (sequence 1), total energy (sequence 2) and total monetary costs (sequence 3), at inception (1 Year) and as a result of hazard exposure over service lives of 10 and 50 years, for Initial Design and two design alternatives.

RESULTS

Figure 2 presents a three-panel visualization using images from the post-processing module (annotated in three sequences to facilitate discussion). Each numbered sequence illustrates the increases in the building's embodied energy (sequence 1), total energy (sequence 2) and monetary costs (sequence 3) due to repairs resulting from hazard exposure for service lives of 10 and 50 years. Each bar chart is further discretized to illustrate the relative contributions of different building assemblies (sequences 1 and 3) or energy measures (sequence 2). An examination of the embodied energy (per square meter) (sequence 1) reveals that the building envelope chosen for the Initial Design is the primary contributor to embodied energy. As a result, the choice of the Alternative Envelope significantly reduces the EE:IC (see results shaded in blue in sequence 1, Year 1), as well as the EE:RM over its service life (see results shaded in blue in sequence 1, Year 50). Figure 2's first sequence also illustrates that the Frame Upgrade results in a higher EE:IC (see Year 1 in sequence 1); though over a service life of 50 years, this choice ultimately results in a lower overall embodied energy due to the reduction of drifts and thereby earthquake-induced repairs over time (see Year 50 in sequence 1). While the Alternative Envelope outperforms other designs from the perspective of embodied energy, this is not the case once operating energy is considered (see sequence 2). The consideration of operating energy reveals that the Frame Upgrade is actually a superior option, due to the Alternate Envelope's larger energy expenditure in operations (see results shaded in blue in sequence 2, Year 1 vs. Year 50). Meanwhile, the monetary costs of each of these options (see sequence 3), considering both construction costs (Year 1), as well as the accumulated cost of hazard-induced repairs over service lives of 10 and 50 years, are driven significantly by the frame and envelope (see results shaded in blue in sequence 3, Year 1 vs. Year 50). As such, while the two design alternatives respectively improve total energy and embodied energy expenditures, the Initial Design requires less up-front investment. Note that the repair costs are not exorbitant, a result of using a highly resilient special moment frame, and these would increase for a more seismically-vulnerable typology. Though difficult to discern in the total costs visualized in sequence 3 due to the high construction cost of the frame, seismic vulnerability was dominated by the envelope, which drove approximately 80% of the annual repair costs in the Initial Design. The selection of an Alternate Envelope reduces annual repair costs by nearly 70%. This illustrative example demonstrates how a more data-informed and comparative conceptual design process could unfold with newfound access to critical resilience and sustainability performance metrics for the building's assemblies.

DISCUSSIONS

Integrating the tools and data from the professions surrounding the design process into a single workflow is challenging, admittedly necessitating simplifications in the models and even examples used herein to vet this workflow. This paper constitutes an important first step to be followed by more faithful case studies sourced from practice. Nonetheless, this illustrative example demonstrates the importance of material choice in design, as embodied energy can be a key driver of environmental impact, particularly over shorter service lives. Moreover, as advances in energy-efficient building systems and non-grid-based energy sources are outpacing advances in efficient material extraction, manufacturing, transportation, and assembly, material embodied energy will be an increasingly larger portion of the total energy balance for the foreseeable future. As such, embodied energy data, and in particular that associated with the repair of hazard-induced damages, will require continued attention within the community. It is anticipated that embodied energy will routinely surpass operating energy once a more complete accounting is possible. Recent studies further suggest that hazard-induced repairs may consume considerably more energy than that embodied in the repair materials themselves (Simonen et al., 2018). While much work remains to truly quantify these impacts, this at minimum underscores the importance of considering not only embodied energy but also its dependence upon hazard exposure in any sustainability evaluation.

CONCLUSIONS

This paper reiterates that a parceled approach, where each discipline optimizes a single performance objective/metric in isolation, does not effectively capture the interrelated concerns of resilience and sustainability. It is worth noting that while these independent concerns may be qualified, their reconciliation is hampered by the lack of a universal metric for comparison, given that sustainability and resilience are quantified in far different "currencies," including even the potential loss of human life. Nonetheless, the integrated LCA presented herein enables a data-informed approach to navigating the inevitable trade-offs between monetary cost, resilience and environmental impact. However, it is important to note that while the Revit-compatible workflow herein is, in and of itself, a significant contribution, its utility will remain dependent on the quality and completeness of the data it relies upon, as well as the ongoing commitment to widely sharing these as linked, open data. The use of semantic data perspectives in the proposed workflow will not only enable the seamless integration of such machine-readable data when it becomes available, but enable a more rigorous geospatial accounting of the life-cycle costs related to the transportation of materials to and from the site. Until that day, the environmental impact of design choices will remain largely speculative. As such, the propagation of uncertainties associated with this source data, as well as those created by the site-specific future hazard/climate exposure and assumptions/simplifications of the wider design process, will be a critical next stage for the authors.

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