# Integrated workflow for evaluating sustainability and resiliency of building systems

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ABSTRACT: This study describes the development of a workflow for integrated life-cycle assessment (iLCA) of buildings that is capable of capturing the dependencies between multi-hazard resilience and sustainability using tools native to professional practice. Modules dedicated to hazard characterization, structural response, damage, repair/loss, and environmental impact (embodied and operating energy) are developed using Application Programming Interfaces (APIs) and semantic data perspectives from computer science. A unifying probabilistic framework is utilized to quantify life-cycle performance and a common, versatile, simulation-based approach is adopted for estimation of performance. This approach supports various resilience/sustainability metrics, including monetary losses, downtime, total embodied energy (initial construction and repairs), and operating energy. A case study executed in the Revit environment evaluates the performance of a special reinforced concrete frame located near Los Angeles International Airport (LAX). Two design alternatives are considered to illustrate the impact of design and material decisions, ultimately revealing design choices which best achieve joint resiliency and sustainability.

## 1. INTRODUCTION

Buildings are responsible for 40% of global energy consumption, placing the building industry at the forefront of efforts focused on reducing environmental impacts worldwide. This has prompted the integration of sustainability assessments into project workflows, with efforts focused primarily on optimizing building operating energy (*OE*). However, the equal importance of embodied energy (*EE*) (the total energy required for material extraction, processing, manufacture, delivery, repair and disposal) has been receiving increased attention (Dixit et al. 2012). *EE* evaluations must acknowledge that the composition of a building is inseparable from its hazard resilience, as the material assemblies which form the building's systems, components, and finishes result in unique vulnerabilities, repair demands, resultant life-cycle costs, and functional recovery times (Gencturk et al. 2016). Unfortunately, it is difficult to factor resiliency into sustainability assessments, as current design practice typically partitions these considerations between the team's engineers and architects. However, given that design choices in material assemblies affect not only a building's response to hazards, but also result in significant environmental impacts due to repairs and can even shorten the building's functional design life, it is imperative to consider resilience and sustainability jointly in the design process through an integrated life cycle assessment (iLCA) to inform the design of resilient, sustainable buildings (RSBs).

The partitioning of sustainability and resilience analyses along disciplinary lines is evident in practice: performance-based engineering evaluations frequently do not support multi-hazard evaluations (except in the case of tall buildings) and, more importantly, ignore environmental impacts (Goulet et al. 2007; Barbato et al. 2013). Meanwhile, sustainability assessments usually focus on *OE*, while the select cases that do consider *EE* impacts, generally neglect the influence of hazard exposure (Rauf and Crawford 2015) and face challenges surrounding incomplete data (Ferguson et al. 2016b). Further, in order for the relevant efforts to translate into faithful iLCAs in the building sector, consideration must be given to the needs of end users in practice. Unfortunately, the interdisciplinary and fast-paced nature of contemporary construction has led to the development of discipline-specific models, datasets, and tools, which each develop a unique abstraction of a building design in order to simplify modeling requirements and allow each discipline to fulfill their design objectives as efficiently as possible. For example, environmental impact tools tailored toward architects (e.g., EnergyPlus, Athena®) often use models which conceptualize the building as a set of enclosed volumes or simply require material quantity takeoffs, while structural analysis tools (e.g., SAP2000®) rely on descriptions of the building that account only for those elements that participate in the primary load path. This limits the interoperability of modeling environments between disciplines, as the underlying data structures supporting these tools deliver incomplete interpretations of the building model when viewed within alternate disciplinary modeling environments. 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, while allowing practitioners to continue working in their native environments. This paper introduces the ongoing research efforts of the authors to mainstream such an approach through a Green Resilience (GR) framework for iLCAs. The following sections present the workflow, including the various modules driving the iLCA, followed by an illustrative example.

## 2. GR FRAMEWORK

### *2.1 Overview of the framework*

The GR Framework, outlined in Figure 1, offers an iLCA that preserves the critical dependencies between multi-hazard resilience and multi-metric sustainability, while supporting the incorporation of normative tools and leveraging open data sources. The impact of hazard resilience on sustainability is explicitly accounted for by the embodied energy of repair materials. Building performance is measured across a suite of resilience and sustainability metrics (monetary cost, downtime, *EE*, *OE*). Conception of the framework is modular and grounded in practice, respectively allowing the flexibility for future refinement and prioritizing integration of practitioner-facing tools. The commercial software Revit© is adopted for the interfacing due to its popularity in practice.

The framework leverages advances in the field of semantic data, specifically through the use of ontology-based data patterns (Ferguson et al.

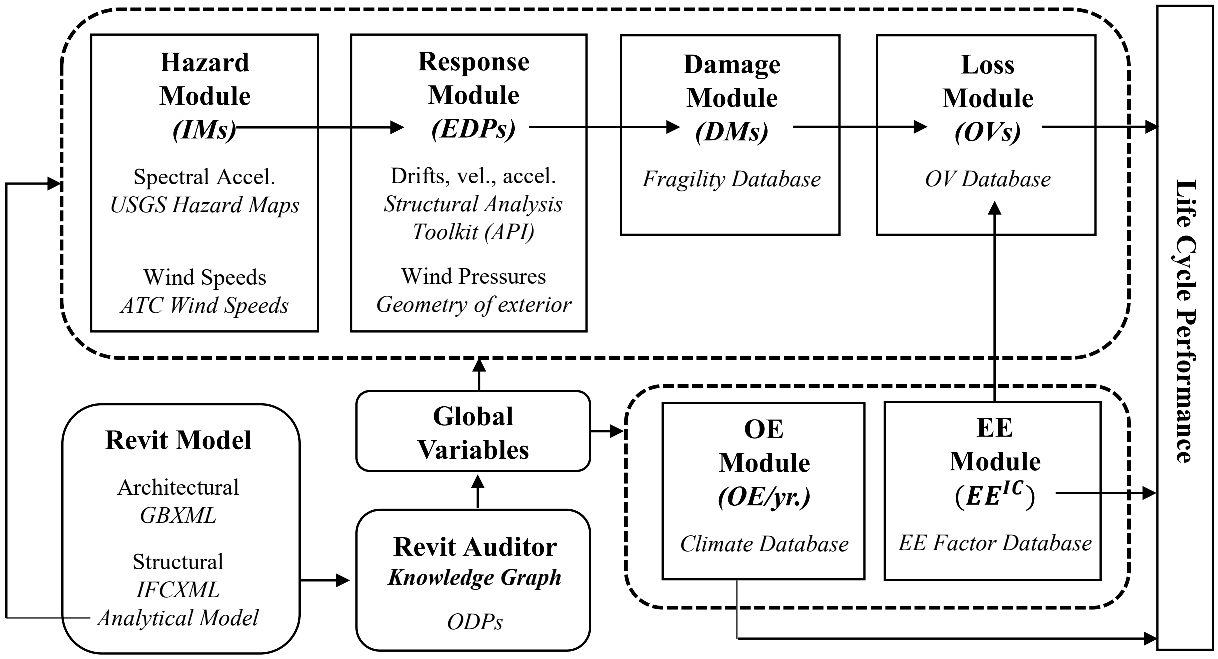


*Figure 1: Schematic overview of GR Framework*

2016a) to (1) seamlessly ingest, assemble, and then rationally process building spatial and material information and (2) facilitate interoperability between distinct schemas inherent to domain-specific tools to achieve interoperability while allowing practitioners to continue working in their preferred computational environments. This is accomplished in the computational workflow through the Revit Auditor, a single parser with the capability to conduct faithful auditing of building information found in various schemas common in the building industry (e.g., gbXML and IFC). The Revit Auditor is able to bridge the gap between interdisciplinary abstractions of the building, using various conceptual and terms mappings to synthesize heterogeneous building information; this data is then published in the form of a query-able semantic "knowledge graph" (Ferguson et al. 2016a). This "knowledge graph" of building information enables the automatic extraction of features and data required by subsequent modules, such as component geometries, material properties, and their location relative to other building elements. Thus, the Revit Auditor's ability to automatically create semantic graphs for various types of BIM files allows the framework to scalably access a more complete description of the building model, storing all extracted data as global variables that can be called upon by various modules in the subsequent workflow. More critically, this minimizes the need to manually extract building information from the BIM environment (Revit) and provides designers with a robust infrastructure for data extraction to support robust evaluations of design alternatives.

### *2.2 Resilience quantification*

Following current PBE standards, resilience quantification is performed using four distinct processes/modules: (1) hazard characterization using a vector of intensity measures (*IM*s), representing salient features of the hazard affecting structural response; (2) a structural analysis to calculate building response to the specified hazard, resulting in a vector of engineering demand parameters (*EDP*s) suitable for assessing hazard consequences; (3) a damage assessment to evaluate structural and nonstructural damage measures (*DM*s), representing indicators of structural condition under these demands; (4) and a loss analysis to relate damage to a set of output variables (*OV*s), representing performance indices of importance to stakeholders, such as monetary cost, downtime or embodied energy due to repairs. Each module is now briefly described.

*Hazard module*: Hazard characterization requires the building location and/or its dynamic properties to identify and parameterize intensities for the corresponding hazards at different return periods (e.g., 500-years). The end product is the hazard curve $\lambda_{IM}(im)$, giving annual frequency of the *IM* exceeding the value *im*. Using relevant APIs, this curve is obtained for seismic hazards from USGS (2018) and for wind hazards from ATC (2018).

*Response Module*: The excitation description from the hazard module and the building properties (e.g., floor-to-floor height, structural system characteristics, building profile, structural envelope) are utilized in the response module to calculate the building's *EDP*s. The EDPs needed for the different hazards, and utilized in this framework, include peak interstory drift ratios, peak absolute acceleration of floors, peak velocity of floors and pressures on the surface of structural and non-structural elements (for wind hazards). To accomplish the objective of a computational workflow that can be integrated with typical design practices, the response evaluation currently relies on static analyses, utilizing an API to interface with SAP2000 (CSI 2018), selected as the structural analysis software due to its wide appreciation among practicing engineers. With respect to incorporation of uncertainties to estimate the probability distribution of $EDP|IM$, an approximate formulation is adopted following (FEMA-P-58 2012): a single building model is utilized, corresponding to the most probable building properties; the distribution for $EDP|IM$ is then taken to be lognormal with median, denoted herein $\underline{edp}(im)$, corresponding to the predictions coming from the response module and dispersion approximated through guidance in the literature (FEMA-P-58 2012).

*Damage module:* For assessing damages an assembly-based vulnerability approach is adopted (Porter et al. 2001), grouping components of the building into assemblies with common vulnerability and consequence characteristics (e.g., structural components, wall partitions, etc.). *OV*s are ultimately (in the loss module) estimated by combining the contributions from each assembly. This approach allows identification of the contribution of individual assemblies to the overall life cycle performance, revealing those most driving resilience or sustainability metrics. In this setting, the damage module evaluates vulnerabilities of building assemblies (structural and nonstructural) to *EDP*s predicted by the response module. Connecting *EDP* to *IM* through the response module, the damage module ultimately provides, for the *i*th damageable assembly, the probability of belonging to each of its damage states $P[DM_i=d_{ik}|IM=im]$; $k=0,\ldots,n_{di}$ (FEMA-P-58 2012).

*Loss module:* The loss module evaluates the desired output variables *OV*s based on the damage state description. Using the assembly-based vulnerability approach the total output is

$$OV = \sum_{i=1}^{n_{as}} OV_i \tag{1}$$

where $n_{as}$ is the total number of assemblies considered and $OV_i$ is the output contribution from the *i*th assembly, which can be estimated based on the output contributions $OV_{ik}$ from each of its damage states $d_{ik}$.

### *2.3 Resilience life-cycle assessment*

The expected value for *OV* for a specific *IM* can be calculated as

$$E[OV \mid IM] = \sum_{i=1}^{n_{as}} \sum_{k=0}^{n_{di}} n_i OV_{ik} P[DM_i = d_{ik} \mid IM] \tag{2}$$

where $n_i$ is the (identical) type of elements belonging to the *i*th assembly. The expected annual statistics for *OV* can be then calculated by

$$E[OV, 1 \text{ year}] = \int_{im_{\min}}^{im_{\max}} E[OV \mid IM] \left| d\lambda_{IM}(im) \right| \tag{3}$$

where $im_{\min}$ and $im_{\max}$ are the minimum and maximum, respectively, values for the hazard *IM* considered. Assuming a Poisson, memoryless process for occurrence of excitation events, the statistics for $t$ years $E[OV|t \text{ years}] = E[OV|1 \text{ year}]$. A similar approach can be employed to calculate variance for *OV* (Goulet et al. 2007) or the distribution of *OV* (Poulos et al. 2017).

### *2.4 Sustainability quantification*

The environmental impact module supporting sustainability quantifications includes evaluation of both the *OE* and *EE*. To perform these assessments, the building is separated through the Revit Auditor (Ferguson et al. 2016b) into sets of spaces, surfaces that make up those spaces, and finally, the individual materials belonging to those spaces. *OE* is calculated using an established thermal model (Yu et al. 2014) to evaluate the building's heat flux; site-specific assessment of the building's *OE* is informed by climatology data. This ultimately allows the estimation of the annual *OE* and its total contribution in $t$ years.

EE quantifications include evaluations of the Embodied Energy in Initial Construction $EE^{IC}$ and the Embodied Energy in Repair Materials $EE^{RM}$. *EE* factors are derived from the University of Bath's Inventory of Carbon and Energy (ICE) database (Hammond and Jones 2008). These factors correspond to specific materials, as open data for individual building elements is usually not available. $EE^{IC}$ is calculated by combining material volumes for each assembly (provided by the Revit Auditor) with cradle-to-gate EE factors and density retrieved from the ICE Database and knowledge graph, respectively.

For estimating $EE^{RM}$, it is necessary to translate repairs for each assembly into measures of environmental impact and ultimately estimate output $EE_{ik}^{RM}$ for each damage state. Unfortunately, while fragility and loss functions in the literature do provide qualitative descriptions of repair actions for the different damage states an assembly may incur due to hazard exposure (FEMA-P-58 2012), these repair actions do not provide a bill of materials for said actions. Therefore, as noted in the review paper by Hasik et al. (2018), other iLCA studies have adopted approximate approaches for the accounting of environmental impact. Here the popular repair-cost ratio approach is adopted. Accordingly, embodied energy for each damage state is taken to be proportional to the $EE^{IC}$ with proportionality derived from the ratio of repair costs to total replacement cost. If $C_{ik}$ is the cost per damage state for assembly *i,* the aforementioned approximation yields:

$$EE_{ik}^{RM} = C_{ik} \frac{EE^{IC}}{C_{in_{di}}}. \tag{4}$$

It should be noted that this calculation of $EE_{ik}^{RM}$ assumes that the materials needed for repair will require the same energy expenditures as the materials in the initial construction (whose embodied energies constitute a cradle-to-gate estimate). Thus, additional embodied energy expenditures, related to disposing of materials as part of the repair (e.g., in the case of repairing the structural frame, the need to cut through interior wall components), are not accounted for in this quantification. Therefore, Eq. (4) should be viewed as a lower bound estimate of $EE_{ik}^{RM}$ .

Finally, use of Eqs. (2) and (3) allows estimation of expected annual embodied energy due to repairs $E[EE^{RM}|1 \text{ year}]$, while the expected total *EE* in $t$ years is then $EE^{IC}+tE[EE^{RM}|1 \text{ year}]$.

## 3. CASE STUDY

Consider a building in Los Angeles employing a two-story reinforced concrete (RC) frame with concrete floor and roof slabs. The building's regular floor plan measures 7 by 9 meters, with top-of-slab elevations at 4.15 and 7.65 meters for floors 1 and 2, respectively. The structural system is a special moment resisting frame, with envelope consisting of infill concrete masonry units with a brick veneer. Gypsum wall board is applied to metal stud partitions at each floor. This section presents the evaluation of this Initial Design from the joint perspective of sustainability and resilience using the GR Framework. Given the negligible effects of wind hazards for this case study, only the results from seismic analyses are presented. Fragility and loss (cost) information are obtained from (FEMA-P-58 2012). All results are described by assembly to inform potential design alterations. To further demonstrate how such assembly-based insights can be used, two design alternatives are respectively evaluated: increasing the size of columns in the frame (termed Frame Upgrade) and selecting an Alternate Envelope using precast RC panels.

Figure 2 presents the life cycle performance of the case study using a three-panel visualization (annotated in three sequences to facilitate discussion). Each numbered sequence illustrates the increases in the building's *EE* (sequence 1), total energy: *EE*+*OE* (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 *EE* (per square meter) (sequence 1) reveals that the building envelope chosen for the Initial Design is the primary contributor to the *EE*. 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

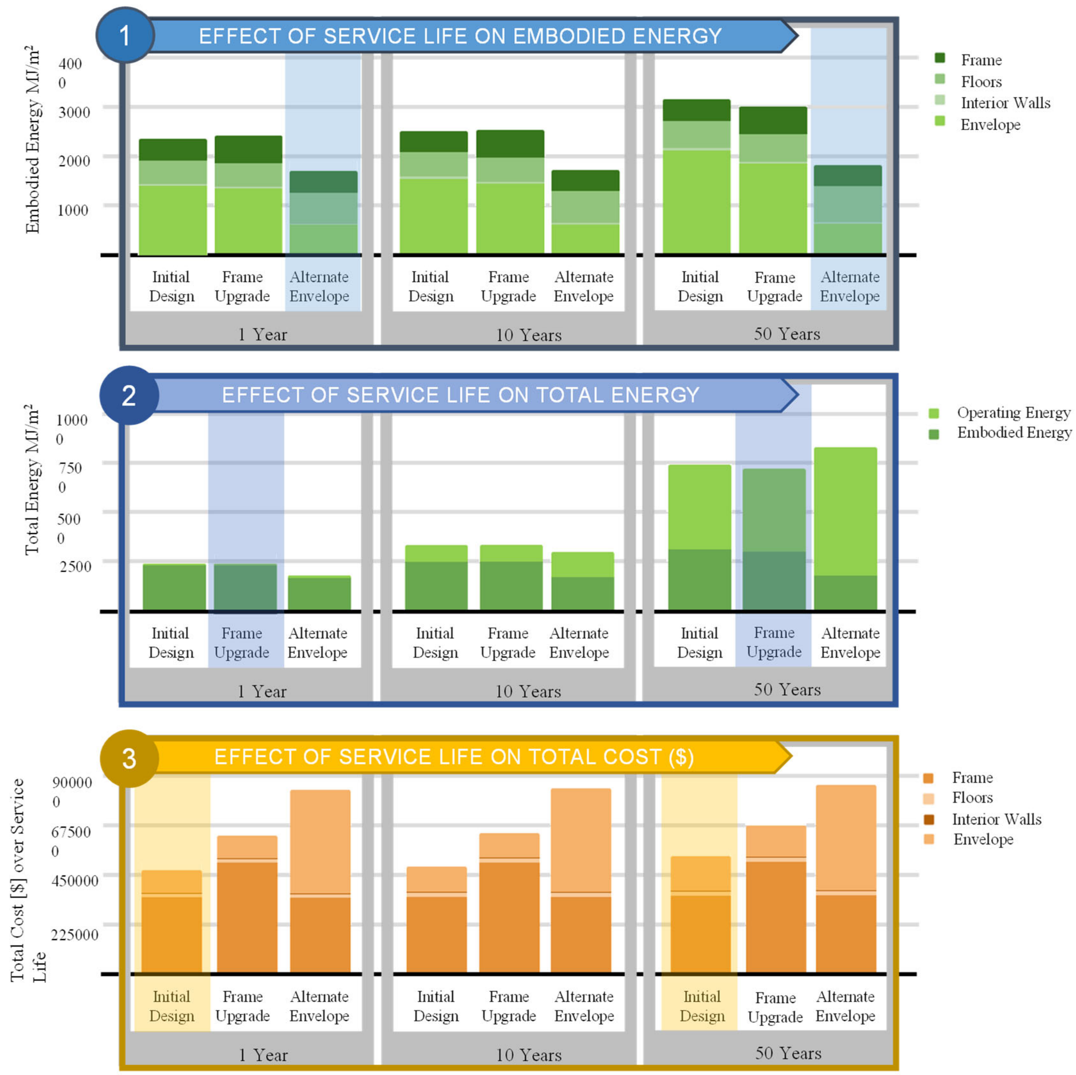


*Figure 2: Annotated visualization of embodied energy (sequence 1), total energy (sequence 2) and total monetary costs (sequence 3), at inception (1 Year) and as a result of hazard exposure over service lives of 10 and 50 years, for Initial Design and two design alternatives.*

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 EE due to the reduction of drifts and thereby earthquake-induced repairs over time (see Year 50 in sequence 1). While the Alternate Envelope outperforms other designs from the perspective of *EE*, this is not the case once *OE* is considered (see sequence 2). The consideration of *OE* 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 *EE* 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 (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%.

Despite the simplifications necessitated by use/integration of tools and data from the professions surrounding the design process into a single workflow, this case study 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. Moreover, this example reinforces the importance of material choice in design, as *EE* 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, *EE* will become an increasingly larger portion of the total energy balance for the foreseeable future. As such, *EE* data, and in particular that associated with the repair of hazard-induced damages, will require continued attention within the community. It should be noted that while this study provides a quantification of the $EE^{RM}$ over the building's service life, hazard-induced repairs may consume even more energy than that embodied in the repair materials themselves. It is anticipated that *EE* will routinely surpass *OE* once a more complete accounting is possible. While much work remains to truly quantify these impacts, this at minimum underscores the importance of considering not only EE but also its dependence upon hazard exposure in any sustainability evaluation.

## 4. CONCLUSIONS

This paper reiterates the consequences of a partitioned approach to life cycle assessments: each discipline optimizes a single performance objective/metric in isolation without effectively capturing the synergies between resilience and sustainability. The integrated LCA presented herein responds by enabling a seamless, data-informed approach to navigating the inevitable trade-offs between monetary cost, resilience, and environmental impact in weighing the myriad of design choices. 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 also 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 will be a critical next stage for the authors' ongoing efforts.

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