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Developing a Decision Framework for Multi-Hazard Design of Resilient, Sustainable Buildings

M.M. Flint[1], L.N.S. Dhulipala, Y. Shahtaheri, H. Tahir, T. Ladipo, M.R. Eatherton, J.L. Irish, C.G. Olgun, G. Reichard, A. Rodriguez-Marek, C. Zobel, R.T. Leon, J.M. de la Garza
Virginia Tech

ABSTRACT

Resilient and sustainable multi-hazard building design can significantly benefit from a holistic approach that considers hazards in the context of the full building life-cycle. Sustainability of a building is dependent not only on well-defined impacts from initial design, construction and operation, but also those associated with uncertain future hazards. Currently available methods are adequate in addressing individual issues related to resilient and sustainable building design but fail in addressing the complexities and interconnectedness in a multi-hazard environment where these dependencies exist at multiple levels. There is a significant knowledge gap in terms of integrated decision support methodologies to reconcile these types of design considerations in a systematic framework. A decision framework under development provides robust estimates of resiliency and sustainability over a broad set of soil, foundation, structural and envelope (SFSE) systems and multi-hazard considerations. Assessment occurs in three modules that perform the following tasks: (M1) generation of site-appropriate SFSE systems; (M2) probabilistic assessment of multi-hazard performance and operation; and (M3) multi-objective and multi-attribute optimization of performance metrics to prioritize and refine the design of candidate systems. The three modules are adaptable and generalizable to multiple building types, hazards, and performance metrics. Building on previous research in performance-based assessment, the decision framework offers a comprehensive and holistic approach to the selection of SFSE systems during conceptual design. Initial development of the decision framework focuses on mid-rise commercial buildings exposed to hurricane, earthquake, and tsunami hazards.

Keywords: multi-hazard, performance-based engineering, optimization, decision-making

1. INTRODUCTION

Buildings and communities are exposed to numerous hazards, including coastal storms and hurricanes, earthquakes and tsunamis, tornadoes, and riverine floods. Traditional engineering practice has designed buildings to resist individual hazard events of a specified frequency; neither the full spectrum of possible events nor the impacts (economic, social, environmental) of the events are explicitly considered. The recent move towards performance-based approaches offers the ability to directly consider uncertainty in the severity of future events as well as resiliency and sustainability metrics. Communities, researchers, and practicing engineers have identified achieving community resilience as a key societal need, motivating efforts to accelerate the transition of engineering practice to a holistic, multi-hazard approach. Given the billions of dollars being spent worldwide in response to natural hazard events, in addition to the likely intensification or increased frequency of some events due to global warming and sea level rise, this transition to an engineering approach that explicitly considers the economic, social, and environmental sustainability of infrastructure must be rapid.

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[1] Corresponding Author: M.M. Flint, *Virginia Tech, mflint@vt.edu*

Furthermore, as described by the National Research Council (NRC 2011), the interdependencies of hazards have made it critical to develop a systems approach to achieve resilient infrastructure and sustainable communities. Interdependencies exist at multiple levels in the way hazards affect the infrastructure and communities (see, e.g., O'Rourke, 2007; NRC, 2011), including interdependencies within building systems and interactions with related lifeline infrastructure. Within building systems, interdependencies occur in three modes: during an individual event; by affecting performance during a subsequent event of the same or different type; and by affecting long-term post-event operation. For example, during a single earthquake performance of the structural system is influenced by non-structural components. Differential settlement of the foundation during an earthquake may result in envelope (façade and roof) damage and decreased moisture resistance in a subsequent storm. This envelope damage may also affect long-term performance by reducing the thermal efficiency of the building envelope, leading to increased energy usage and higher costs for heating and cooling.

A multi-disciplinary team is working to develop a decision framework capable of predicting the resiliency and sustainability of building systems. The framework is composed of three independent modules, and combines advanced analysis of multi-hazard performance and operation with optimization and decision analysis. In addition to its comprehensiveness, the novelty of the proposed framework resides in its intended use in the early or conceptual design phase. Implementing performance-based approaches during early design is difficult due to the lack of knowledge of design details and the need to facilitate rapid analysis over a broad array of possible building configurations. Early design is also critical as it offers the most effective opportunity to increase building sustainability (as found by, e.g, Basbagil et al. 2013, among others). The decision framework being developed will compute quantitative metrics that can be used to evaluate building system resilience and sustainability during early design. The decision framework also offers a feasible method to achieve community performance targets, an area of active research, see e.g., recent efforts by Mieler et al. (2015) to develop community performance targets and to link these targets to individual building resiliency. Current development efforts are focusing on mid-rise commercial buildings exposed to hurricane, earthquake, and tsunami hazards.

This paper introduces the decision framework and envisions its further development. Section 2 provides motivation, lays out objectives, and provides an overview of the current framework conceptualization. Section 3 describes the methodology associated with the three assessment modules, including brief reviews of related work. Section 4 describes research questions to be addressed. Section draws conclusions with regard to the significance, applicability, and limitations of the framework.

2. PROPOSED DECISION FRAMEWORK

A fundamental assumption is key to the decision framework: a number of different building and subsystem configurations have the potential to perform optimally at a given site across resilience and sustainability metrics. The potential for multiple optimal systems occurs because of the multi-objective, multi-criteria nature of the decision-making process. Some systems may reach equal values of a single metric by trading off between contributing factors: one building may have high initial cost but low operational cost, whereas another may have the inverse. Other systems may make tradeoffs between different metrics: low cost and high energy usage versus the opposite. These metrics will be accrued from the multiple subsystems that make up a building: soil, foundation, structure, and envelope (SFSE). The overarching purpose of the decision framework, then, is to identify SFSE systems that have the potential for optimal performance at a given site.

Fig. 1 illustrates three example SFSE systems that are expected to perform optimally at a given site by achieving different balances across metrics and construction and operation phases. The buildings are assumed to have the same general plan and are exposed to high flood hazard and moderate earthquake hazard. The building site has poor soil conditions (class E) and sits in a local depression, thereby increasing the risk of flooding. System A elevates all building entrances above a given floodplain elevation, and designs the basement and envelope to resist water intrusion and to minimize flooding effects. To mitigate the seismic hazard, System A uses a mat foundation and includes no soil improvement. A combined structure and envelope system of a reinforced masonry mass wall cannot experience incompatible structure and envelope deformations during a seismic event. System B improves the soil to increase the potential for drainage as well as to reduce ground motion and deformation. This improvement allows the construction of a more standard building design, with a reduced mat foundation supporting a steel moment frame and a glass curtain wall.

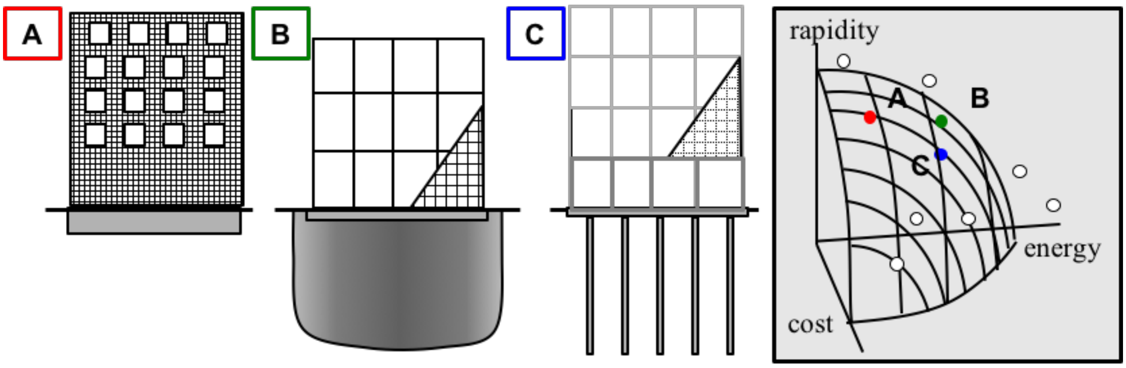

Figure 1. Three example SFSE (**s**oil, **f**oundation, **st**ructure, **e**nvelope) systems expected to perform optimally across sustainability and resiliency metrics. The Pareto front (right) compares optimal systems (closed circle) with non-optimal systems (open circles).

System C is supported by drilled piers, which allows significant elevation of the first story to reduce flood hazard. Light frame structural and envelope construction will be effective during earthquakes. The Pareto front shown in the right-hand portion of Fig. 1 illustrates the hypothetical optimality of these three systems. For each system any improvement in one decision metric would require a worsening of another metric. The three example systems achieve different balances of rapidity/downtime (low preferred), life-cycle cost (low preferred), and embodied energy (low preferred). The identification of such optimal systems is the primary purpose of the decision framework being developed.

2.1 Objectives

The decision framework targets a series of objectives related to its intended use and desired characteristics. For a given site, the decision framework must be able to identify the best SFSE system(s), where best can be described as the most resilient and sustainable system that meets the needs and preferences of the owner or developer. The status of "best" must be judged according to a set of quantitative sustainability and resiliency metrics. The final ranking of the systems must be performed according to stakeholder preferences: given the SFSE systems shown in Fig. 1, System A might be identified as the preferred, as the owner might not be able to pay the high upfront costs for System C, and might be unwilling to undertake the significant soil improvements required by System B. Further, it must be possible to use the decision framework during the early or conceptual design phase.

The framework must also attain several characteristics that will increase its potential for adoption. It must account for the full spectrum of events produced by multiple hazards and their interactions, as well as the operational phase of the building. The framework should be generalizable and expandable: able to accommodate new SFSE subsystems, building types, hazards, or performance metrics. Finally, the framework must allow for the substitution of models in each of the three assessment modules. While methodologies are being developed for each of the three modules, it should be possible to implement different approaches, e.g., the use of an alternate optimization approach in Module 3. The characteristic of "modularity" also increases conceptual clarity while reducing computational expense (as interactions between modules are limited). Furthermore, modularity also ensures that each of the three modules could independently serve as a design aid.

2.2 Overview of decision framework

As shown in Fig. 2, the decision framework is composed of three modules: (M1) an SFSE system generator; (M2) a multi-hazard performance assessment; and (M3) a set of optimization algorithms. Required inputs are owner preferences and constraints and a general building characterization, including dimensions and number of stories. The modules support three assessment paths. An initial assessment identifies a set of SFSE systems that meet decision-maker preferences and are optimal for the site based on resiliency and sustainability metrics (A1, solid line). If these systems are not satisfactory, the decision-makers may update their constraints and preferences and perform another assessment (A2, dotted line). Optionally, optimization may be performed on satisfactory systems to refine their designs or to optimize repair and recovery strategies (A3, dashed line).

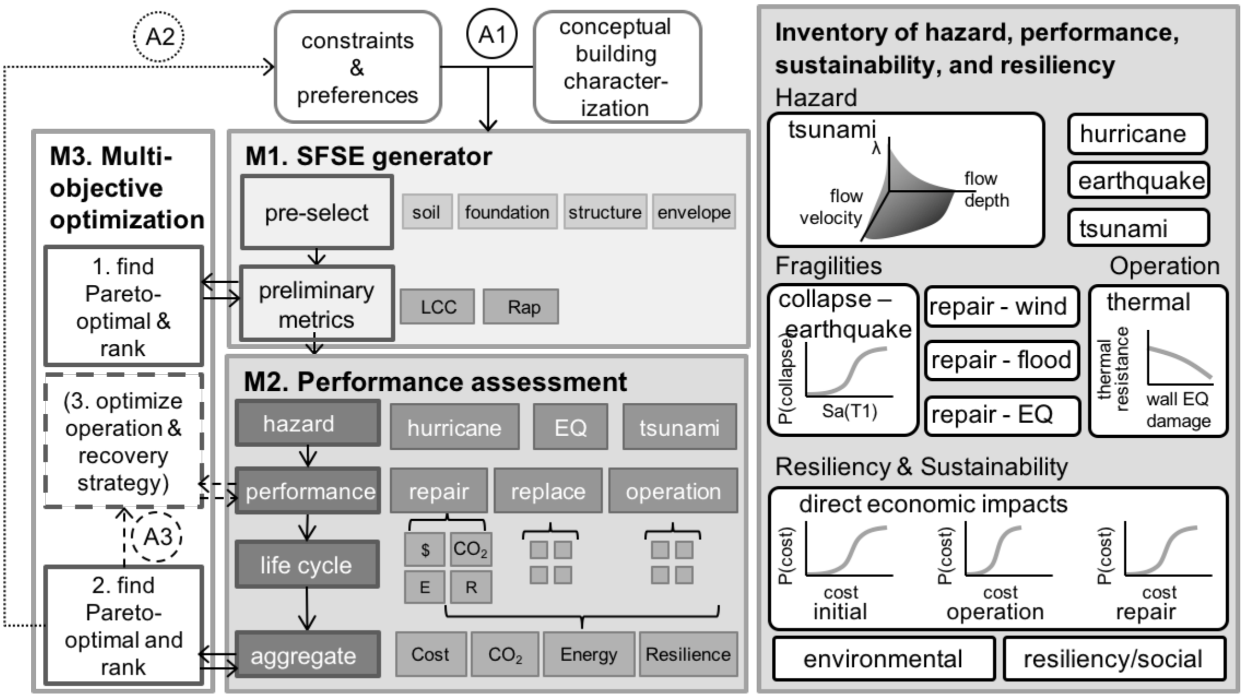

Figure 2. Assessment flow through the three-module decision framework, including inventory of hazard, performance, and life-cycle metric data (upper portion).

The framework must limit computational expense to find traction in the early design phase. This limit on computational expense is achieved by increasing the level of analysis detail as the number of candidate SFSE systems considered decreases. While the number of systems considered would be selected by the user, it is envisioned that Module 1 might produce on the order of 100 candidate SFSE systems, of which optimal configurations would be generated, resulting in 1000 SFSE systems moving to Module 2. Each of the 1000 systems would undergo performance assessment, and Module 3 would identify a limited number, say 3, potentially preferred systems. If the additional optimization runs are undertaken, those 3 might be expanded to 10 considering different operation and recovery strategies or different configurations of the SFSE subsystems. It is therefore critical that Module 2 limit computational expense to the degree practical, and that the algorithm(s) used in Module 3 are capable of finding optimal systems both when a large number of systems are considered (e.g., after Module 2), and when only a few configurations are considered (e.g., during the optional recovery strategy optimization). In addition to limiting computational expense, this approach offers the benefit of supporting sensitivity assessment at multiple points in the analysis.

3. ASSESSMENT MODULES

3.1 SFSE generator

This module identifies combinations of Soil, Foundation, Structure, and Envelope (SFSE) subsystems that: (1) meet the requirements of the owner/developer; and (2) are expected to achieve high performance at the site.

3.1.1 Related work

A number of qualitative design guides, reconnaissance reports, and performance-based approaches have been used to identify building systems that perform well or poorly under the effects of a variety of hazards. Design guides such as FEMA 452 can be used to identify interdependencies between building systems (FEMA 2005). Post-hazard reconnaissance reports documenting the effects of hazards can be used to identify critical failure modes and subsystem interdependencies. Such reports are available for hurricanes (e.g., Tomiczek et al., 2013), earthquakes (e.g., by Sarabandi et al., 2004), and tsunamis (e.g., Charvet et al., 2015). Numerous performance-based assessments have analyzed archetype structures that reflect the range of design parameters for a particular building type. These archetype analyses are intended to bridge the gap between performance of a specific building and the generalized predictions of performance for a class of buildings. To support such assessments, many datasets and tools have been developed, including PACT, the "Performance Assessment Calculation Tool" (FEMA 2012b), which calculates losses related to earthquake-induced building damage.

3.1.2 Proposed methodology

Existing methodologies and available literature for performance-based engineering for hurricanes, earthquakes, and tsunamis will be used to develop an inventory of the performance of generic/archetypal SFSE systems. When possible, this inventory will be collected from studies using methodologies performance-based engineering (PBE) linked to the PEER framework for performance-based earthquake engineering (PBEE) developed by Cornell and Krawinkler (2000), among others. Such approaches break up the performance assessment by connecting a series of analyses at "pinch-points," at which one analyses produces a limited number of variables that are used as inputs to the next analysis. Generic "pinch-point variables" can be customized as appropriate to the particular combination of hazard and structure type analyzed. Intensity Measures (IMs) represent the severity of the action of a hazard event at the building site (e.g., spectral acceleration or flow velocity). Engineering Demand Parameters (EDPs) are obtained by simulating structural response during the hazard events (e.g., story drift ratios or envelope deformation). Damage States (DSs) are qualitative descriptions of the sort of damage in a building component that can be produced by a level of a given EDP (e.g., light cracking of gypsum wallboard). Decision Variables (DVs) are metrics associated with repair or replacement of a component in a certain DS (e.g., cost or downtime). A nomenclature is being developed to identify and partition pinch-point variables applicable to the SFSE subsystems across hurricane, earthquake, and tsunami hazards.

In the original PEER and related approaches to PBE, the integration (convolution) of a series of conditionally-independent probabilistic distributions is used to compute the annual expected values of decision variables over the range of possible events. Conditional independence is a mathematical necessity requiring that the probability of observing a certain value of a pinch-point variable is related only to the immediately prior pinch-point (e.g., DV must depend only on DS and not EDP). To date four categories of conditionally independent probabilistic distributions have been collected, with a focus on earthquake assessments. The distributions link: IMs to collapse; IMs to EDPs; EDPs to DSs; and DSs to DVs. Data related to tsunami and hurricane performance is also being collected. FEMA P-58 has been a major source for the component fragilities and the life cycle metrics (FEMA 2012a). The distributions are being critically reviewed to differentiate between distributions (e.g., fragility curves) developed from test data or from engineering judgement. Possible techniques to improve test data collection have also been identified.

3.1.3 Future work

Data collection will focus on a set of SFSE subsystems that are particularly applicable to mid-rise commercial buildings. Data related to three soil systems (unimproved, reinforced, modified), four foundation systems (single footing, continuous footing, mat footing, drilled piers/driven piles), and eleven structural systems (cold formed steel shear walls, steel eccentrically braced frame, steel, concentrically braced frame, steel buckling restrained braced frames, steel plate shear walls, steel moment frames, reinforced concrete moment frames, reinforced concrete shear walls, pre-cast concrete shear walls, wood shear wall, reinforced masonry shear walls) is being collected. Not considering envelope systems, 132 SFS systems would theoretically possible. Various checks (e.g., compatibility of structural and foundation system) has reduced this set to 92 potentially viable SFS systems. Classification and selection of envelope systems is ongoing.

3.2 Performance assessment

The module assesses: (1) multi-hazard exposure; (2) SFSE system performance before and after hazard events; (3) life-cycle metrics associated with construction, operation, repair, and recovery.

3.2.1 Related work

Most performance assessment approaches consider regional infrastructure portfolios, archetype structures, or the detailed design phase. Regional or archetypal approaches support disaster planning and retrofit policy, and are not intended to support the early-design decisions that are critical to achieving sustainability and multi-hazard resiliency. Portfolio-based approaches, such as Hazus-MH (produced by FEMA, 2011), RiskScape (by Schmidt et al., 2011), CAPRA (by CEPREDENAC, 2014), the Global Earthquake Model (GEM) (by Meslem et al., 2014), and Parameterized Fragility based Multi-Hazard Risk Assessment (PF-MHRA, for bridges) (by Kameshwar and Padgett, 2014), among others, excel at predicting regional response to natural disasters. Alternately, performance-based approaches, e.g. those developed by FEMA P-58 (FEMA 2012a), McCullough and Kareem (2011), Li and Ellingwood (2009), Cornell and Krawinkler (2000), Barbato et al. (2013) and Flint et al. (2014), assess the design of a single structure across a spectrum of event or exposure intensities. Due to their high complexity and computational expense, these approaches are not routinely implemented in the design process. Performance-based assessments used in practice, e.g., in the design of tall buildings (e.g., SEAONC 2007), require the development of highly complex nonlinear models and do not usually consider as large a spectrum of event intensities as traditionally used in research.

Many of the data and methods developed for use in regional or detailed-design assessments apply to the proposed decision framework and may be adaptable to the needs of conceptual design. As described in Section 3.2.2, the performance assessment proposed for use in Module 2 shares many similarities with the PEER framework for performance-based earthquake engineering and related frameworks (e.g., those by Cornell and Krawinkler, 2000, Barbato et al., 2013, Flint et al., 2014). Research into probabilistic seismic, tsunami, and flood hazard analysis (e.g. by Cornell, 1968; Geist and Parsons, 2006; Irish and Resio, 2013) and ground motion selection (e.g. by Baker 2011) will inform the methodology developed for Module 2. Nonlinear incremental dynamic analysis (IDA) of multi-degree-of-freedom (MDOF) or single-degree-of-freedom (SDOF) structures are frequently used in performance-based assessments and will likely be used in the decision framework. Many analyses of archetype buildings provide additional data. Furthermore, while the capacity curves developed for Hazus-MH are not directly compatible with IDA, methods have been developed to translate those curves into deteriorating SDOF backbone curves (by Karaca and Luco, 2008, and Ryu et al. 2008), which are then compatible. Capacity curves were developed for Hazus-MH for a variety of structural systems, and are described by design level (i.e., conformance to building codes of different eras), and by construction quality. To translate structural response to damage and loss, databases of fragility curves and loss curves (e.g., the Performance Assessment Calculation Tool, PACT, FEMA 2012b) were developed and will be included in the decision framework data inventory (Fig. 2).

To assess operation and the decision metrics, other sources of data and methods are required. Many open-source tools are available, such as building energy simulation tools (e.g., US Department of Energy's EnergyPlus software), building-focused life-cycle assessment tools (e.g., US National Institute of Standards and Technology's BEES--Building for Environmental and Economic Sustainability--software), and models of recovery and resilience such as those developed by Zobel and Khansa (2014), and Burton et al. (2015). A method for producing equivalent resiliency/recovery curves in multi-event histories developed by Zobel and Khansa (2014) is expected to be especially helpful in computing resilience and rapidity (downtime) metrics.

3.2.2 Proposed methodology

Module 2's performance assessment links exposure to operational performance and hazard response and then to sustainability impacts; impacts accrued across the spectrum of possible hazards must then be aggregated according to their likelihood of occurring. These steps line up with the pinch-points and method for integrating conditionally independent distributions proposed in the PEER framework for PBEE. However, given the requirements of the decision framework discussed in Section 2.1, especially the need to maintain compatibility with conceptual design, Module 2 must extend and modify the PEER approach, as shown in Fig. 3.

Compatibility with conceptual design indicates that the use of a fully-specified building model to determine EDPs (as used in other performance-based approaches) is not feasible due to: (1) lack of complete design information, and (2) the need to cover broad space of SFSE systems and configurations. It is therefore proposed to separate the EDP pinch-point in two: first an EDP reflecting a simplified, equivalent version of the system (SEDP), and second the mapping of the simplified response the real, multi-component structure (MEDP). SEDP can be described by analyzing a simple model that does not require undue computational expense or too many design details. However, this simple model is unlikely to be capable of producing EDPs at the component level, preventing the direct analysis of component-level damage states. By mapping the equivalent simple system response to a more complete representation of the system response, full sets of component response can be simulated, thereby supporting component-level damage and loss estimation.

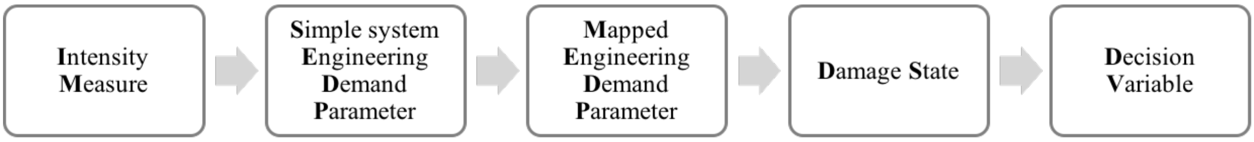

Figure 3. Pinch-points of Module 2 performance assessment

3.2.3 Future work

Current development of the Module 2 methodology is focused on developing the simple equivalent system models as well as methods for mapping their response to that of the full, multi-degree-of-freedom system. A methodology for simulating earthquake response using deteriorating nonlinear single-degree-of-freedom (SDOF) oscillators subjected to recorded ground motions is currently being investigated. SDOF backbone curves translated from Hazus-MH capacity curves, using a methodology developed by Karaca and Luco (2008), and Ryu et al. (2008), show promise in producing acceptably accurate results while maintaining low computational expense. Preliminary analyses are being conducted to identify potential simple, equivalent models for building exposure to the wind, surge, wave, and scour aspects of hurricane loading. Results of these analyses will be used to determine whether or not nonlinear models for each of the subsystems is required, and whether or not dynamic analysis must be conducted.

The consideration of multiple, as opposed to single, hazard types requires the development of new assessment methods. Specifically, the Module 2 performance assessment must account for interaction of hazards and interrelated subsystem performance. While it would be possible to simulate a number of potential futures for the structures using a brute-force Monte Carlo approach, with each potential future having different numbers of events/event types, and thereby avoid all issues related to conditional independence, it is expected that such an approach would be prohibitively computationally expensive. The development of more efficient methods, which may or may not follow the PEER conditionally-independent distribution approach, is underway.

3.3 Multi-objective optimization

This module: (1) identifies potentially optimal SFSE systems using the resiliency and sustainability metrics produced by Module 1; (2) ranks the systems using the metrics produced by Module 2; and (3, optionally) optimizes repair and recovery strategies.

3.3.1 Related work

Complex decision-making problems (as described by Shoghli, 2014), apply a multi-objective decision making (MODM) algorithm to simultaneously optimize several conflicting objectives. An MODM problem with k objectives can be defined as follows in Equation 1 (Marler, and Arora 2004):

$$Z(x^s) = [Z_1(x^s), Z_2(x^s), \cdots, Z_k(x^s)] \tag{1}$$

where x is an n-dimensional decision variable vector and can be defined as $x = \{x_1, \ldots, x_n\}$. In the presented equation x is the vector that optimizes the k objectives. Because some objectives may be conflicting, optimization will minimize some objectives whereas others will be maximized.

Exact or metaheuristic multi-objective optimization can be applied to MODM problems. Exact optimization can be achieved through the use of linear or nonlinear optimization functions. As an extension of linear programming, goal programming has been used in asset management for addressing multi-criteria condition assessment of bridges (Ravirala et al. 1996). Two-dimensional project scheduling problems (of time and cost) with nonlinear cost functions, and pavement preservation optimization with multiple objectives have been solved using nonlinear programming (Klansek, 2015; Moussourakis and Haksever, 2010; Wu and Flintsch, 2009). Metaheuristic algorithms are frequently based on animal behavior and are more emphasized in large scale construction management problems. Metaheuristics are high level frameworks for searching the decision space which include simulated annealing (SA), genetic algorithm (GA), particle swarm optimization (PSO), ant colony optimization (ACO), and shuffled frog-leaping (SFL). While the effectiveness of metaheuristic algorithms might vary for different asset management problems, they have been used in MODM due to their ability to handle nonlinear, constraint, discontinuous, multi-modal optimization models (Liao et al. 2010). Shoghli (2014) addresses a four objective optimization problem of time, cost, level of service and environmental impact using ACO. Additional studies by Elbeltagi et al. (2005) compare evolutionary-based optimization algorithms for continuous and discrete optimization problems, considering processing time, convergence speed, and the quality of results.

3.3.2. Decision metrics

Five metrics are currently being considered for inclusion in the decision framework: life-cycle cost (LCC), greenhouse gas emissions (GHG), embodied energy (EE), level of resilience (LoR), and rapidity (Rap). LCC considers initial construction, operation, and recovery costs. EE focuses on the material types and volumes used to construct an SFSE system, whereas GHG additionally considers energy consumption. Bruneau et al. (2003) describe resilience as having four characteristics of robustness, redundancy, resourcefulness, and rapidity. Robustness, rapidity, and the overall resilience are considered (directly and indirectly) in the LoR and Rap metrics. Robustness relates to the ability of the structure to resist the initial impacts of the natural hazard event. Resilience has been defined by Burton et al. (2015), among others, as the area beneath a recovery curve, which measures how the function of a building is reduced after an event and gradually recovers. The time until full functioning is restored can then be defined as downtime or rapidity (Rap).

3.3.3 Proposed methodology

As discussed in Section 2.2, two (optionally three) levels of optimization are supported by the decision framework. The first level of optimization (Equation 2) will be conducted on metrics produced by Module 1 (M1). This optimization minimizes life-cycle cost (LCC) and rapidity (Rap) for each candidate SFSE system with respect to various design options and hazards. The second level of optimization (Equation 3) will be conducted on the more specific performance metrics produced by Module 2 (M2). In addition to LCC and Rap, this optimization will consider GHG, EE, and LoR. The relative importance of each of the decision metrics at each level of optimization will be defined using weights that reflect decision-maker values and preferences.

$$Z(x^s) = [LCC_{M1}(x^s), Rap_{M1}(x^s)] \tag{2}$$

$$Z(x^s) = [LCC_{M2}(x^s), GHG_{M2}(x^s), EE_{M2}(x^s), LoR_{M2}(x^s), Rap_{M2}(x^s)] \tag{3}$$

3.3.4 Future work

The scope of the future research includes: finalizing the decision variables for Modules 1 and 2; characterizing the decision space; defining the optimization framework; and testing the optimization algorithm(s) with scalable test problems.

4. FUTURE RESEARCH QUESTIONS

In addition to the plans for future work related to each of the three modules, future development of the decision framework will address both fundamental and specific research questions, including:

- What is the most generic possible characterization of the performance of a SFSE system (Module 1)?
- How can the performance of a SFSE system be characterized as specifically as possible within the limits of conceptual design and computational expense (Module 2)?
- What is the impact of variable uncertainty among hazards and metrics, or combination of aleatory and epistemic uncertainty, on the identification of optimal systems?
- How critical is recovery strategy in minimizing the life-cycle sustainability and resiliency metrics associated with SFSE system performance?

5. CONCLUSIONS

A decision framework to support conceptual design of resilient, sustainable buildings exposed to multiple hazards is being developed. The decision framework considers both the construction and operation impacts traditionally considered in life-cycle assessment as well as impacts related to natural hazards. Current development efforts focus on mid-rise office buildings exposed to hurricanes, earthquakes, and tsunamis. In addition to its comprehensive nature, the framework is modular, and therefore highly generalizable and expandable. Envisioned applications include analysis of novel soil, foundation, structural, or envelope systems, extension to multiple building types (e.g., residential), introduction of other hazards, and expansion of the decision metrics.

Many challenges remain in the further development of the decision framework, related both to the methodologies associated with the three modules as well as more general research questions. Additionally, the current structure of the framework introduces some important limitations. By focusing on a single building in isolation from its surroundings, the framework neglects important (and frequent) causes of building failure. For example, at this time the decision framework would not be capable of correctly analyzing a situation in which the failure of external infrastructure, e.g., transportation, limits building function. This limitation will become more critical as community-based tools for resilience assessment are developed. However, the decision framework is expected to make an important contribution towards the use of performance-based and optimization tools in practice through its focus on conceptual design. It is also anticipated that the decision framework could be highly useful to future research effort due to its comprehensive multi-hazard approach and capabilities in sensitivity assessment.

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